

Vol. XXII.—No. 129]

[June, 1930.

THE
MINERALOGICAL MAGAZINE
AND
Journal of
The Mineralogical Society

(INSTITUTED FEBRUARY 3, 1876.)

WITH A SEPARATELY-PAGED APPENDIX OF
MINERALOGICAL ABSTRACTS

EDITED BY L. J. SPENCER, F.R.S.

ABSTRACTORS

F. N. ASHCROFT.
F. A. BANNISTER.
H. E. BUCKLEY.
P. N. CHIRVINSKY.
T. CROOK.
A. F. HALLIMOND.
M. H. HEY.
HAROLD HILTON.
E. D. MOUNTAIN.

A. L. PARSONS.
G. T. PRIOR.
W. A. RICHARDSON.
S. J. SHAND.
F. SLAVÍK.
W. CAMPBELL SMITH.
L. J. SPENCER.
K. ZIMÁNYI.
V. ZSIVNY.

LONDON:

HUMPHREY MILFORD, OXFORD UNIVERSITY PRESS,
AMEN HOUSE, WARWICK SQUARE, E.C. 4.

—
1930.

Price 6s. net.

Annual Subscription for four numbers, Post free 20s.

MINERALOGICAL SOCIETY

Officers and Council for 1929-30.

PRESIDENT.

G. T. PRIOR, M.A., D.Sc., F.R.S.

PAST-PRESIDENTS.

Sir HENRY A. MIERS, M.A., D.Sc., LL.D., F.R.S. (1904-1909).	Prof. A. HUTCHINSON, O.B.E., M.A., Ph.D., F.R.S. (1921- 24).
A. E. H. TUTTON, M.A., D.Sc., F.R.S. (1912-1915).	Prof. W. W. WATTS, M.A., M.Sc., Sc.D., LL.D., F.R.S. (1924-27).
W. BARLOW, F.R.S. (1915-1918).	

VICE-PRESIDENTS.

Sir JOHN S. FLETT, K.B.E., M.A., LL.D., D.Sc., F.R.S.	G. F. HERBERT SMITH, M.A., D.Sc., F.G.S., F.R.A.S.
--	---

TREASURER.

F. N. ASHCROFT, M.A., F.G.S., F.C.S., 1 Egerton Gardens,
South Kensington, London, S.W. 3.

GENERAL SECRETARY.

W. CAMPBELL SMITH, M.C., T.D., M.A., F.G.S., *British Museum of
Natural History, South Kensington, London, S.W. 7.*

FOREIGN SECRETARY.

J. W. EVANS, C.B.E., LL.B., D.Sc., F.R.S., *Geophysical
Company Limited, 62 London Wall, London, E.C. 2.*

EDITOR OF THE JOURNAL.

L. J. SPENCER, M.A., Sc.D., F.R.S., *British Museum of
Natural History, South Kensington, London, S.W. 7.*

TRUSTEES.

F. N. ASHCROFT, M.A., F.G.S., F.C.S.	Sir HENRY A. MIERS, M.A., D.Sc., LL.D., F.R.S.
---	---

ORDINARY MEMBERS OF COUNCIL.

Col. N. T. BELAIEW, C.B., F.C.S.	Prof. W. G. FEARNSIDES, M.A., F.G.S.
A. BRAMMALL, Ph.D., M.Sc., F.G.S.	
A. J. BULL, M.Sc., F.Inst.P., F.G.S.	Prof. HAROLD HILTON, M.A., D.Sc.
H. COLLINGRIDGE, B.Sc., F.G.S.	Prof. ARTHUR HOLMES, D.Sc., F.G.S.
Prof. C. G. CULLIS, D.Sc., F.G.S.	W. F. P. McLINTOCK, D.Sc., F.G.S.
G. McDONALD DAVIES, M.Sc., F.G.S.	Miss M. W. PORTER, B.Sc.
HENRY DEWEY, F.G.S.	

LIBRARIAN.

Miss J. M. SWEET, B.Sc., *British Museum of Natural History, South
Kensington, London, S.W. 7* (to which address all publications in-
tended for the Library of the Society should be forwarded).

Bankers.—Messrs. Coutts & Co., 15 Lombard Street, London, E.C. 3.

THE MINERALOGICAL MAGAZINE

AND

JOURNAL OF THE MINERALOGICAL SOCIETY

No. 129.

June, 1930.

Vol. XXII.

*Some mineralogical and chemical changes induced by
progressive metamorphism in the Green Bed
group of the Scottish Dalradian.*

(With Plate X.)

F. COLES PHILLIPS, M.A., Ph.D., F.G.S.
Fellow of Corpus Christi College, Cambridge.

[Read November 5, 1929.]

INTRODUCTION.

THE petrology of the igneous rocks has for the last quarter of a century been established on a sound quantitative basis, largely as a result of the body of experimental work available on silicate melts. In the field of metamorphism, however, progress has been much less marked, and the difficulties of the laboratory development of stresses comparable with those acting during regional metamorphism must for some time leave our knowledge of the crystalline schists far behind that even of the hornfelses. A quantitative approach, however, is not confined to the experimental side. The introduction of the conceptions of facies and grade¹ raises a new need for exact knowledge of the compositions of the various minerals, both of those constituting the different isophysical assemblages of a given grade, and of the isochemical assemblages representing a given rock under the grade-conditions of the various facies established. The need is for fuller chemical investigation, where possible, of individual minerals

¹ P. Eskola, *Norsk Geol. Tidsskr.*, 1920, vol. 6, pp. 143-194; C. E. Tilley, *Geol. Mag.*, 1924, vol. 61, pp. 167-171.

as well as of the rock in bulk.¹ With increasing knowledge of the effects on optical properties of the various components which enter into solid solution in natural minerals it is becoming increasingly possible to determine a mineral accurately from optical data, so that where actual separation is not feasible a full statement of these data, even for the commonest constituents, is of value.

The universal stage affords the readiest means of carrying out a full investigation of individual crystals in a thin section, yet it is still regrettably rare for a petrologist to avail himself of this opportunity in routine descriptive work. In the felspar group, much work has been done on the well-formed phenocrysts in andesites and allied igneous rocks, but application of the method even to this group of minerals in the crystalline schists is practically untouched. The account presented below is to be regarded as an indication of desirable lines of research, rather than as a complete contribution in itself.

GENERAL CHARACTER OF THE GREEN BEDS.

The Green Beds of the Scottish Dalradian succession form a series of widespread development which is readily distinguishable by marked characteristics, and has the advantage of occurring in an area in which the zoning of progressive metamorphism as determined in pelitic rocks rests on a fairly firm basis.² From their characteristic bedding and jointing, intercalated pelitic bands, lateral passage into other types, and the frequent presence of pebbles of quartz they are readily seen, at least in the lower grades, to be of sedimentary origin; yet they possess distinctive chemical characteristics, most readily explained by fairly direct derivation from basic igneous rocks and deposition without much admixed material. In proportion as the amount of foreign material increases, they pass from their own distinctive isochemical group towards normal psammitic or pelitic rocks. This view was long ago put forward by the Geological Survey,³ but the published evidence seems to consist of a single analysis of a rock from Ardlui, Loch Lomond.⁴ Five new analyses have therefore been obtained of material from various grades, (Anal. I-V), and with these is quoted the Survey analysis. The first glance reveals wide variation in the silica-content, a constituent whose passive role

¹ C. E. Tilley, *Min. Mag.*, 1926, vol. 21, p. 46.

² C. E. Tilley, *Quart. Journ. Geol. Soc. London*, 1925, vol. 81, pp. 100-112.

³ *Mem. Geol. Survey, Scotland*, Sheet 37, 1905, p. 18.

⁴ *Geol. Survey Summary of Progress for 1903, 1904*, pp. 57-58.

in many metamorphic changes has been emphasized.¹ The essential chemical resemblances and differences are more readily appreciated if the Niggli values for *al*, *alk*, *fm*, *c* and *k*, *mg* are calculated (Table II) and plotted (figs. 1 and 2). The *si* numbers, of course, show considerable variation (112–353), but the points in the *al-alk-fm-c* tetrahedron fall close together, and within the field of composi-

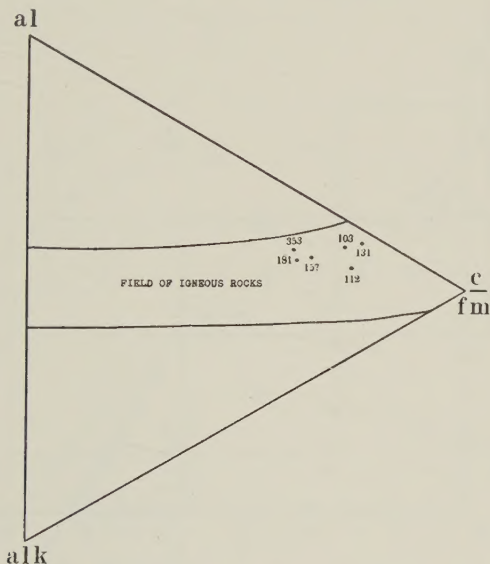


FIG. 1. Plot of analyses I–VI on section of the *al-alk-fm-c* tetrahedron.

tion of igneous rocks in a position corresponding in general to a gabbro magma-type. The close resemblance of analysis VI to that of many 'diabases' was pointed out by Sir J. S. Flett; the clustering of the points in fig. 1 brings out well the essentially isochemical character of the series under investigation.

Sediments of Green Bed character occur at several horizons in the outer part of the Dalradian succession, but the main development is between the Loch Lomond and Loch Tay series, not far below the Loch Tay Limestone. A zone in which they occur abundantly, though with intercalations of other sediments, can be followed more or less continuously from Kintyre north-eastwards to Glen Clova, in

¹ C. E. Tilley, *Min. Mag.*, 1926, vol. 21, p. 38.

which direction it thins gradually. Its non-appearance farther north-east than Glen Clova might be due to various causes, and no evidence at present available enables a decision to be made.¹ During this course the Green Beds pass gradually from the lowest grades just to the kyanite-sillimanite boundary, as determined in pelitic sediments. In the higher grades their separation from the intrusive rocks with which they are frequently associated is often difficult, but crushed

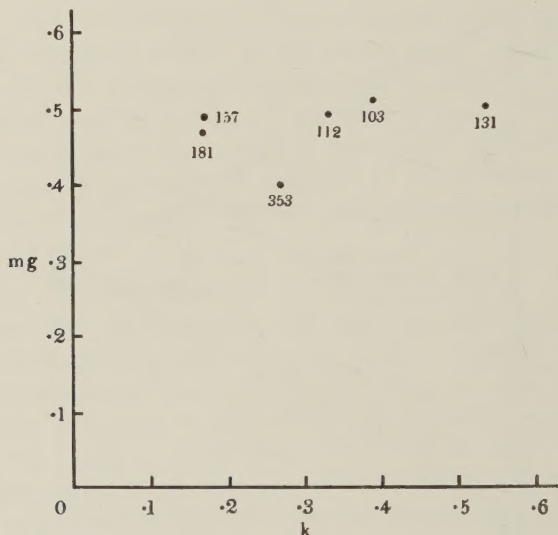


FIG. 2. *k-mg* diagram for analyses I-VI.

sills usually show a more lenticular structure, inconstant jointing, and rusty weathering. A sketch-map is appended, showing their approximate distribution in relation to the one-inch maps of the Geological Survey (fig. 3).

No extended account of the Green Beds as a group has been published. They receive attention in the various official memoirs covering the areas in which they occur (see especially those for sheets 37, 46, 47, 55, and 65), and in many of the Summaries of Progress issued during the mapping (particularly from 1897-1903). They are also referred to briefly in many publications on the tectonics of the Dalradian area, and on the regional metamorphism of this and other districts.

¹ H. H. Read, Trans. Roy. Soc. Edinburgh, 1928, vol. 55, p. 770.

GENERAL ACCOUNT OF PROGRESSIVE METAMORPHISM.

The chlorite zone.

In its lowest grade of metamorphism the typical Green Bed presents itself as a chlorite-albite-epidote-schist. Abundant *chlorite*, to

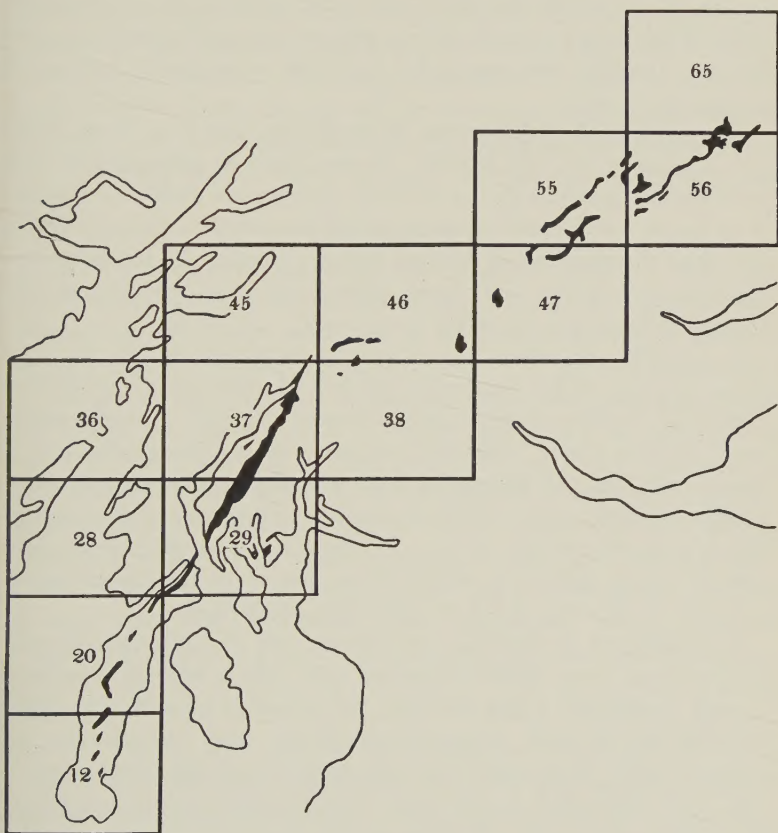


FIG. 3. Sketch-map showing the approximate distribution of the Green Beds in relation to the one-inch maps of the Geological Survey.

which the colour of the rock is mainly due, occurs as long lath-shaped crystals or as scaly aggregates. It is of greenish-yellow colour, but the depth of colour and strength of pleochroism are quite variable; where larger crystals wrap around opaque iron-ores they often acquire a deeper colour and stronger pleochroism from green to

yellow. The double refraction rises slightly, too, and whereas much of the material may be sensibly isotropic these areas give deep brownish-purple anomalous interference colours. Occasionally the chlorite builds stumpy porphyroblasts set across the schistosity.

The *albite* occurs as rounded crystals showing considerable variation in size, the structure varying from strongly porphyroblastic to equigranular; and in finer aggregates with quartz in the groundmass. Many of the larger crystals show a cloudy zone of inclusions in the interior; lamellar twinning is not common, occasionally a trace of zoning can be seen.

The amount of *epidote* varies fairly widely, and from many slides it is almost or entirely absent. It may occur as aggregates of pale yellow-green granules giving a cloudy appearance under low powers, or as larger well-formed crystals, yellowish-green to greenish-brown and often showing zoning between crossed nicols. Its irregular distribution in streaks and bands often shows up prominently the original sedimentary character of the rock.

A variable and often large quantity of *quartz* is seen in most slices, and the larger lenticular patches of partially recrystallized aggregates sometimes obviously represent original quartz pebbles partly broken down. Opaque iron-ores—magnetite, pyrite, and a titaniferous iron-ore associated with granular sphene—rutile, idiomorphic apatites, and occasional tourmaline needles are all accessory minerals of the normal rock. A carbonate mineral is frequently present, and its habit and relationships suggest in many cases that it is a primary mineral of the metamorphic assemblage.

A constituent of sporadic occurrence, but notably abundant in certain types, is an almost colourless *mica*. Even when present only in very occasional flakes amongst the chloritic ground it is easily detected by its high polarization-colours, and examination in ordinary light then usually reveals that it is distinctly coloured a very pale green, and is pleochroic between this tint and colourless. In extreme cases this coloration approaches that of a pale chlorite. The mica is finely divided and evenly distributed throughout the groundmass; in types in which it becomes more abundant it contributes to a felted structure of the whole micro-section.

The appearance of a dark mica in these low-grade rocks signalizes a slightly increased grade of metamorphism, but begins well below the biotite isograd of pelitic rocks.¹ Its first appearance is usually

¹ C. E. Tilley, Quart. Journ. Geol. Soc. London, 1925, vol. 81, p. 103.

as small green-brown streaks bridging larger chloritic patches and readily distinguished by their more pronounced pleochroism. As it becomes more abundant, it acquires a deeper colour and a pleochroism from yellow-brown to a deep brownish olive-green. It usually follows the schistosity closely, but may also form radiating sheaves, or more rarely be set in porphyroblasts across the cleavage. In these the elongation is much less, cross-sections being practically square; lines of epidote granules may continue the schistosity through these porphyroblasts. The early appearance of biotite may be seen in the middle of the chlorite zone in the south-west, on the shores of Loch Striven; and again farther north-east in numerous localities in the neighbourhood of Loch Lubnaig and the eastern half of Loch Earn.

The biotite zone.

As described above, the Green Beds begin to develop a dark mica considerably in front of the biotite isograd in pelitic rocks, and the passage into the biotite zone itself is not marked by any pronounced new mineral development. In all the rocks of normal composition biotite is now an abundant constituent, and from localities farther north-west, in the direction of higher grade, as, for example, in material from the head of Hell's Glen, Cowal, it can be seen to be acquiring a more brownish tinge, marking a gradual approach in appearance to the normal red-brown mica. In the more melanocratic rocks chlorite is still present, often deeply coloured and strongly pleochroic, but it is scarce or absent in the case of more gritty varieties. A rock from Ballochandrian, near Glendaruel, Cowal, may be described in detail, as a partial mineral separation has been carried out (p. 251); the bulk analysis is given (anal. I). The rock is coarse-grained and gritty, with abundant quartz in rudely lenticular patches. Greenish biotite, with pronounced elongation, forms crystals up to 1 mm. long. The other important dark mineral is a yellow epidote in granular aggregates tending to occur between the more quartzose patches; chlorite is practically absent. The fairly abundant albite shows a strong tendency to porphyroblastic habit, with lamellar twinning not uncommon and occasionally a very slight degree of zoning. Calculation of an approximate mode gives quartz 54, epidote 20, albite 14, and biotite 12 %.

Less siliceous varieties from this zone show the usual accessories, and passage types a similar type of greenish muscovite to that described from the lower-grade rocks above.

The garnet zone.

The Green Beds are found within the garnet zone in the south-west near Loch Tarbert and Loch Fyne, and pass again completely across the zone in Perthshire. With their considerable variations in composition, they may themselves show the almost immediate development of garnets; as, for example, near the junction of the Cur and the Cab, south of Strachur, Loch Fyne (memoir for sheet 37, p. 20), and west of Loch Fender, Amulree; but the areal distribution of garnet is decidedly irregular and single thin sections may show it confined to narrow bands. Biotite is fairly constantly present, and is now a more brown or typical red-brown colour. Hornblende now becomes important, usually with a marked acicular habit, and only occasionally as platy crystals, which latter sometimes show zonary extinction. The colour and pleochroism are fairly constant, and the γ axial tint in particular is characteristic; α yellowish, β brownish-green, γ bluish-green. The extinction $\gamma : c$ is usually about 20° .

Epidote, sometimes accompanied by zoisite, is present only in diminished amount, and may be associated with the biotite in eyes and lenticles. Chlorite may have survived in small amounts, sometimes intergrown with the biotite; a colourless mica is rare. Clastic structures are not often seen, except where large pebbles remain as patches of recrystallized quartz; the structure is pronouncedly schistose. In the dominantly hornblendic types, however, the garnets do not usually form the centres of marked eyes, this appearance being confined to the micaceous examples.

Higher zones.

Between Pitlochry and Kirkmichael the Green Beds run in the broad expanse of the garnet zone in this district, and pass on the south-west side of Glen Clova within the higher zone of kyanite and just up to or across the boundary with that of sillimanite, but do not themselves show the development of aluminium-silicate minerals. The texture becomes increasingly coarse, and hornblende is the predominant or only ferromagnesian mineral, and it is here that great difficulty is experienced in separating them from doleritic intrusions. A pebbly example from the south of Caddam, Clova, shows small rounded garnets in certain layers only. The felspar is now an oligoclase or andesine (p. 250).

The feldspars.

It was early established that of the plagioclase isomorphous series the pure albite end-member is a characteristic stress mineral, whilst anorthite is anti-stress.¹ In low-grade dynamic metamorphism the reconstituted feldspar is a pure albite, but as the metamorphic grade increases a more calcic member of the series becomes stable. From this view-point a special study has been made of the composition of the plagioclases of the Green Beds by means of the universal stage.

The newly-developing conception of the facies classification of metamorphic rocks is vitally concerned with the degree to which equilibrium is maintained in the various mineral assemblages, and such rocks as the Green Beds are suggested as indicators,² in view of their apparently high sensitivity to changes of temperature and stress. The first sets of measurements were therefore made on duplicate slides of material, both in the case of low- and high-grade localities, and suggest that so far at least as the feldspars are concerned the adjustment to equilibrium is close. Within the chlorite zone no feldspar has been measured showing more than 3 or 4 % of anorthite, which within the limits of error of the method can be considered pure albite. A succession of measurements of material from Glen Clova showed a composition constant between the limits 29–35 % of anorthite.

Much of the feldspar is of course untwinned, but results can always be obtained from measurements of cleavages or (much less reliably) the optic axial angle $2V$. Twinning when present is usually simple, the complicated twinning of the phenocrysts of igneous rocks being rarely if ever observed. It is rare, too, to find association on more than two laws in a single crystal, and of these laws a high percentage are well-known twins. As in igneous rocks, twins associated on (010) are usually much the commonest, and of these albite twinning the most frequent. The pericline twin, however, becomes important much nearer the albite end of the series in these metamorphic rocks than is the case in igneous rocks, and this fact is likely to lead to error in determination by orthodox methods.³ The percentage frequencies of the various laws as observed in these Green Beds are for all the measurements: albite 60, pericline 17,

¹ F. Becke, Denkschr. Akad. Wiss. Wien, Math.-naturw. Kl., 1913, vol. 75, pp. 42–43.

² C. E. Tilley, Quart. Journ. Geol. Soc. London, 1923, vol. 79, p. 200.

³ F. Coles Phillips, Min. Mag., 1930, vol. 22, p. 225.

Carlsbad 16, and other laws 7%. Of the pericline twins, however, 80 % contain more than 25 % anorthite.

The cleavages are sometimes interesting, for the good cleavages (001) and (010) of idiomorphic feldspars are less frequently seen in these porphyroblasts than a cleavage (110) or a series of cracks approximating to this direction. A similar observation has been made by Carstens,¹ who attempts to correlate rarity of the (001) and (010) cleavages with the surface forms of the porphyroblasts. The same writer found in general no parallel arrangement of the feldspars. Though no attempt has yet been made to investigate this systematically in the case of the Green Beds on the lines developed by Sander and Schmidt,² work with the universal stage makes it quite apparent that there is some regularity of arrangement. If a particular section happens to be so cut that for the first feldspar investigated two particular axes such as α and β can be directly determined, then it is frequently found that the majority of the other feldspars of that section will give the same pair. Schmidt has found a similar regularity in feldspars as well as in quartz.³

Two other features in the feldspars call for comment. The reconstituted albite is usually water-clear except for foreign inclusions, which are often zonally arranged. Occasionally, however, a feldspar is seen which shows between crossed nicols a variety of wavy, perthitic, or chequer intergrowth; in some cases the pattern of these is extremely regular, but no intergrowth of two minerals could be seen in ordinary light, even with careful manipulation of the condenser and diaphragms. Becke described similar appearances in chequer-albites,⁴ where newly-formed albite is homoaxially arranged in conjunction with original potash-feldspar. He describes the similarity of oblique sections to sections of anorthoclase, and the frequent presence of a later fringe of normal twinned albite, both of which features have been observed in the feldspars of the Green Beds and confirmed by universal stage measurements. No case has been seen, however, in which an obvious difference of refractive index between the two feldspars (if such they be) could be observed, nor has it so far proved possible to correlate the presence of these possible chequer-albites with any indications of a potassic character in the rock.

¹ C. W. Carstens, *Norsk Geol. Tidsskr.*, 1924, vol. 7, pp. 241-242.

² W. Schmidt, *Min. Petr. Mitt. (Tschermak)*, 1925, vol. 38, pp. 392-423.

³ W. Schmidt, *Neues Jahrb. Min., Abt. A*, 1928, Beilage-Band 67, pp. 203-222.

⁴ F. Becke, *Denkschr. Akad. Wiss. Wien, Math.-naturw. Kl.*, 1913, vol. 75, p. 125.

The zoning of feldspars in metamorphic rocks also first received detailed attention from Becke, who demonstrated that very frequently the zonary arrangement is the reverse of that familiar in crystallization from a melt, a more albitic kernel being surrounded by a more anorthitic shell. The Green Beds of the lowest grades contain nearly pure albite, in which there is no measurable zoning, although in many sections the extinction is not quite uniform throughout each crystal. Where an oligoclase or oligoclase-andesine becomes stable a moderate degree of zoning is sometimes present; and, by measurements of optical orientation, optic axial angles, or extinctions from determined directions, it was confirmed that the core was less anorthitic than the outer shell, with differences of composition of the order of a few per cent. of anorthite. A similar reversed zoning has been observed by Carstens in his material from the Trondhjem district.¹ As the observations of Becke have not been always confirmed by later writers, one possible cause of failure to detect the true direction of the zoning may be suggested. A frequent combination of twinning in the oligoclase-andesines of the Green Beds is multiple pericline twinning, with rare albite lamellae making with the pericline lamellae an angle of less than 90°. If cleavage is not visible and the direction of frequent twinning be assumed as the (010) direction, orthodox determinations of extinctions would give a reversed interpretation of the zoning over a certain range of composition.

Grubenmann and Niggli² have put forward an explanation of this reversal in terms of the solubility relationships of the plagioclases. Anorthite being the more soluble, pure albite will separate first from aqueous solutions, and anorthite will thus be successively enriched outwards. With a given kernel, more of the soluble anorthite will pass into solution, and on the Riecke principle will crystallize out in places of low pressure. Becke has himself observed that the calcic shell does not always completely surround the acid core, but may be developed on one or two sides only.

Composition of the plagioclases.

It has been observed that the plagioclase throughout the lower grades is uniformly albite. Measurements have been made on

¹ C. W. Carstens, loc. cit., p. 242.

² U. Grubenmann and P. Niggli, *Die Gesteinsmetamorphose*, I. Berlin, 1924, p. 425.

material from various localities in the chlorite zone in the districts of Loch Katrine, Strathyre, and Loch Earn, and in slightly higher grades from Ballochandrian, Balquhiddy, &c. The anorthite molecule only begins to enter noticeably into the composition of the plagioclase when the garnet isograd is passed. Measurements of material from localities around West Loch Tarbert, Loch Fyne, and south of Aberfeldy give compositions of $\text{Ab}_{95}\text{An}_5$ to $\text{Ab}_{90}\text{An}_{10}$. As the grade increases farther, the plagioclase is taking part actively and the composition changes rapidly. The most calcic feldspars measured occur near the summit of the Hill of Strone, south-west of Glen Clova (2778 feet), near the kyanite-sillimanite boundary, with a composition of $\text{Ab}_{63}\text{An}_{37}$, medium andesine. At the north-east side of Glen Clova, near Loch Brandy, the average composition of a large number of measurements was $\text{Ab}_{68}\text{An}_{32}$.

It is interesting to compare with these results a series of measurements on the feldspars of the associated epidiorite sills. Though of closely similar composition to the Green Beds chemically, they differ in the important feature that they represent a high-temperature association only partly accommodated to low-temperature conditions.¹ In the lowest grades, the original feldspar has undergone saussuritic change, and the plagioclase now present is pure albite, but the calcic portion is represented by epidote, zoisite, &c., usually forming a core of inclusions in the albite. The change in the Green Beds from a chlorite-albite-epidote assemblage to that of hornblende and plagioclase is paralleled in these rocks by the gradual re-absorption of the calcic minerals to give a more calcic plagioclase. The actual compositions of the feldspars are closely similar in the two series; averages for the epidiorites are: St. Catherine's Ab_{100} , Balquhiddy $\text{Ab}_{95}\text{An}_5$, Kinloch Rannoch $\text{Ab}_{83}\text{An}_{17}$, Pitlochry $\text{Ab}_{76}\text{An}_{24}$, Glen Clova $\text{Ab}_{63}\text{An}_{37}$.

MINERALOGICAL CHANGES ON METAMORPHISM.

It has been observed that the Green Beds in their lowest grade consist mainly of recrystallized chlorite, with lime present largely as epidote, pure sodic feldspar, and a white mica in the more pelitic varieties. One of the earliest changes is the production of a green-brown biotite. The genesis of biotite at this stage usually involves interaction of chlorite and sericite, and in these highly chloritic rocks the available sericite is often rapidly consumed. It has been suggested,

¹ C. E. Tilley, *Geol. Mag.*, 1924, vol. 61, p. 170.

in fact, that the mica-like mineral which forms in rocks low in potash is not a true potash-mica, but the optically similar stilpnomelane.¹ A separation was carried out on a rock from Ballochandrian, Cowal (p. 245) and the greenish-brown material analysed (Anal. VII, p. 255).

In view of the urgent need of many more analyses of this kind, it may be valuable to outline the methods of separation employed. The particular rock was chosen as being fairly simple in mineralogical constitution, but the chief difficulty lay in the inconsistent behaviour of the dense but flaky mica, which ruled out the use of heavy liquids. The average grain of the rock was measured in thin sections, and a quantity crushed to a mesh-size likely to avoid composite grains. This material was then run through a Hallimond magnetic separator, and the medium magnetic concentrate, already largely mica, put through a second time. The chief foreign material at this stage was granular epidote, and an effective separation was achieved by the use of a glazed pasteboard tray, perforated at one corner, as a primitive 'shaking-table'. A small quantity of the concentrate was spread along one side of the tray, which was then tapped rapidly by the fingers of one hand, whilst held slightly inclined. The granular epidote travelled more rapidly over the surface than the tabular mica and could readily be manœuvred to fall through the perforation in advance of the latter. Finally, the material was picked over, a small quantity at a time, under a binocular microscope, and any foreign grains removed on a moistened camel-hair brush.

The mineral is a true potash-mica, fairly high in ferric iron; its composition can be represented almost exactly by a Tschermak mixture of muscovite and olivine. Quite comparable analyses are recorded by Doelter.² The refractive index, γ 1.63, was determined by immersion and accords fairly well with the graph given by Grout,³ who also notes that a green colour in a mica is at least suggestive of a considerable content of ferric oxide. (Compare the reverse change, from brown to green, on weathering, without lowering of the double refraction.)

In the subsequent change of the biotite towards the normal red-brown tint it is customarily assumed that there is an increase of the FeO content.⁴ It has not yet been found possible to effect a satisfactory separation of a mica of this type, which tends to occur as poorly-developed crystals in rocks of fairly complex mineralogical constitution. An impure specimen separated from a garnetiferous rock from Pittiely Burn, south of Duntagart, east-south-east of Aberfeldy, gave an FeO content of 15.8%, and a refractive index γ greater than

¹ A. F. Hallimond, *Min. Mag.*, 1924, vol. 20, p. 196.

² C. Doelter, *Handbuch der Mineralchemie*, 1917, vol. 2, part 2, p. 691.

³ F. F. Grout, *Amer. Min.*, 1924, vol. 9, p. 163.

⁴ C. E. Tilley, *Min. Mag.*, 1926, vol. 21, p. 40.

1.63. Analysis VIII is that of a biotite from a high-grade rock, from the Hill of Strone, but the colour in this case is a greenish-brown allied to that of the low-grade mineral.

It has been noted that garnet is sporadically developed. Dr. Tilley has argued that the normal genesis of almandine in pelites is from chlorite, often with exchange of magnesia for ferrous oxide.¹ The variable degree to which excess of chlorite survives and recrystallizes in higher zones may be correlated with this variability of occurrence of garnet. An analysis of a garnet from a garnetiferous hornblende-schist from Dalnacarn Craig, near the Kirkmichael road, five miles north-east of Pitlochry, is given (Anal. IX), and shows a molecular ratio of FeO to MgO of 3.1, with lime figuring equally prominently with magnesia.

In carrying out separations on these high-grade rocks, a magnetic separator or the usual heavy liquids were employed initially to remove the lightest minerals. For the final separation it was found that very good results could be obtained by means of fused mercurous nitrate. If a quantity of the salt was allowed to melt undisturbed in a large boiling-tube immersed in a water-bath, a diffusion-column with small differences of density was established. When the concentrate had been gently poured in, the boiling-tube was revolved between the palms of the hands about a vertical axis, and under the action of the slight disturbance thus set up in the melt the minerals arranged themselves in sharply-defined layers. In this way, for example, the garnet was obtained practically pure as a layer separated by an inch of the solidified salt from the darker ferro-magnesian minerals above and below it. The difference of colour made removal of the few foreign grains by hand-picking an easy matter, yielding an absolutely pure garnet concentrate.

Hornblende normally appears after garnet, and represents the calcareous content which contributed to the formation of epidote in earlier stages, this latter mineral now disappearing. At this stage, too, the albite, which has remained practically unaffected, begins to give place rapidly to a plagioclase containing notable amounts of the anorthite molecule:

epidote + albite $\rightarrow$ amphibole + more calcic plagioclase.

Dr. Tilley has discussed the genesis of hornblende in green schists, and has shown that the potash-content is important in determining the grade of its first appearance. In the non-potassic green schists of the Start, South Devon,² as in the altered spilites of Cornwall³

¹ C. E. Tilley, loc. cit., 1926, pp. 43-44.

² C. E. Tilley, Quart. Journ. Geol. Soc. London, 1923, vol. 79, p. 185.

³ F. Coles Phillips, Geol. Mag., 1928, vol. 65, p. 554.

and Finland,¹ hornblende appears before biotite. With admixed sericitic material, as in a tuff or derived sediment of the nature of the Green Beds, the higher potash-content leads to the formation of biotite, and hornblende appears much later, often after garnet, as noted in the petrographic descriptions above. In this connexion material from localities in the Loch Earn district is of special interest. Rocks from Creagan nan Gabhar, south of Loch Earn, and from the south side of Loch Boltachan, one mile north of St. Fillans, Loch Earn, although occurring in the middle of the chlorite zone of pelitic rocks, show the development of an amphibole. The mineral is finely fibrous, pale green or almost colourless (and lacking the characteristic blue-green axial tint of the hornblende of higher-grade rocks), with positive elongation and marked oblique extinction. A bulk analysis of one of these rocks is given (Anal. II), and shows a molecular ratio for CaO to K₂O of 27, this ratio for the Cowal rock (Anal. I) being only 8. An alkali estimation of the other Loch Earn rock showed a K₂O content of only 0.41.

CONCLUSION.

The tracing of these changes progressively on passing from south-west to north-east may serve as an excuse for pleading in conclusion that renewed attention should be paid to the significance of the Older Granite intrusions. Mr. Barrow wrote in 1912² 'the Highland area, south of the Caledonian Canal, is essentially built up on the lines of an aureole of metamorphism round a granite intrusion; but instead of aureoles we have zones or belts which diverge more and more from a . . . highly crystalline nucleus'. This simple view has been combatted, but the reduction of the Older Granites to 'merely an incident'³ may tend to obscure the fact that they represent the focus of high temperature and high pressure conditions. An interesting comparison has been effected between this Dalradian area and the Jutogh series near Simla, India.⁴ The metamorphic changes in the latter series are essentially regional in character, but a modifying zonal relationship can be traced within the region influenced by the Chor granite. Dr. Harker, writing of normal regional metamorphism, has recently shown how 'the zones recognised are primarily temper-

¹ P. Eskola, *Fortschr. Min. Krist. Petr.*, 1927, vol. 11, pp. 63-66.

² G. Barrow, *Proc. Geol. Assoc. London*, 1912, vol. 23, p. 277.

³ C. E. Tilley, *Quart. Journ. Geol. Soc. London*, 1925, vol. 81, p. 112.

⁴ G. E. Pilgrim and W. D. West, *The structure and correlation of the Simla rocks*. *Mem. Geol. Surv. India*, 1928, vol. 50, pp. 60-72.

ature-zones',¹ and how, though the metamorphism is essentially regional in kind, the bounding lines are in a certain sense isothermals.

A considerable portion of the expenses of analyses in connexion with this work has been met by a grant from the Royal Society. I wish also to record my indebtedness to Prof. A. Hutchinson and Dr. A. Harker for encouraging and assisting the investigation in many ways: to Dr. C. E. Tilley and Mr. W. D. West for supplying me with hand-specimens, and to Mr. W. Campbell Smith for initial instruction in the use of the universal stage.

Table I. *Rock analyses.*

		I.	II.	III.	IV.	V.	VI.
SiO ₂	...	73.25	50.80	58.90	46.10	56.20	48.28
TiO ₂	...	0.35	1.26	1.02	1.90	1.17	1.37
Al ₂ O ₃	...	10.06	14.21	14.28	17.42	15.26	13.20
Fe ₂ O ₃	...	2.80	4.57	1.08	3.47	3.75	2.60
FeO	...	2.44	6.49	8.28	9.73	6.40	11.35
MnO	...	trace	0.40	0.13	0.44	0.22	0.77
MgO	...	1.88	6.08	4.58	7.60	5.25	7.67
CaO	...	5.14	10.55	4.40	9.18	6.38	7.35
Na ₂ O	...	1.80	0.36	3.64	1.36	3.30	2.63
K ₂ O	...	1.08	0.66	1.09	1.28	1.05	2.02
H ₂ O—	...	0.10	0.20	0.50	nil	0.30	0.07
H ₂ O+	...	1.00	3.58	1.90	1.60	0.70	2.14
CO ₂	...	nil	0.72	nil	nil	nil	0.91
P ₂ O ₅	...	trace	trace	0.05	trace	0.05	0.21
S	...	trace	nil	trace	nil	trace	0.03
Cr ₂ O ₃	...	—	—	—	—	—	0.02
(Co,Ni)O	...	nil	nil	nil	nil	nil	0.04
V ₂ O ₅	...	—	—	—	—	—	0.05
		99.90	99.88	99.85	100.08	100.03	100.71

- I. Biotite-epidote-albite-schist, near Ballochandrian, west of Glendaruel river, Cowal, Argyllshire. Anal. W. H. Herdsman.
- II. Epidote-biotite-hornblende-schist, south side of Loch Boltachan, one mile north of St. Fillans, Loch Earn, Perthshire. Anal. W. H. Herdsman.
- III. Garnetiferous biotite-hornblende-schist, Pittiely Burn, ESE. of Aberfeldy, Perthshire. Anal. W. H. Herdsman.
- IV. Garnetiferous hornblende-schist, Dalnacarn Craig, Kirkmichael road, five miles NE. of Pitlochry, Perthshire. Anal. W. H. Herdsman.
- V. Hornblende-biotite-plagioclase-schist, Glen Clova, Forfarshire. Anal. W. H. Herdsman.
- VI. Biotite-hornblende-schist, west side of railway cutting, $\frac{1}{4}$ mile north of Ardlui station, Dumbartonshire. Anal. W. Pollard.

¹ A. Harker, *Fennia* (Helsingfors), 1928, vol. 50, no. 36, pp. 6-7.

Table II. *Niggli values of rock analyses.*

Analysis.	si.	al.	fm.	c.	alk.	k.	mg.	c/fm.	Section of Tetrahedron.
I.	353	28.5	33.5	26.5	11.5	0.27	0.40	0.80	V.
II.	131	22.0	47.0	29.0	2.0	0.54	0.50	0.61	IV.
III.	181	26.0	45.5	15.0	13.5	0.17	0.47	0.32	III.
IV.	103	23.0	50.0	22.0	5.0	0.39	0.51	0.44	IV.
V.	157	25.0	45.0	19.0	11.0	0.17	0.49	0.42	III.
VI.	112	18.0	55.0	18.0	9.0	0.33	0.49	0.33	III.

Table III. *Mineral analyses.*

			VII.	VIII.	IX.
SiO ₂	...	...	38.14	38.20	38.40
TiO ₂	...	...	0.23	1.72	nil
Al ₂ O ₃	...	...	16.92	18.57	21.28
Fe ₂ O ₃	...	...	7.37	1.73	6.07
FeO	...	...	11.25	13.23	21.34
MnO	...	...	0.53	nil	2.84
MgO	...	...	9.84	14.93	3.75
CaO	...	...	1.27	1.85	6.30
Na ₂ O	...	...	0.20	3.01	-
K ₂ O	...	...	7.60	4.88	—
H ₂ O—	...	...	(6.65)	0.10	trace
H ₂ O+	...	...		1.60	
			100.00	99.82	99.98
Sp. gr.	...	...	—	—	4.00
Refr. index	...	...	1.63	—	1.80

VII. Green biotite, Ballochandrian, Cowal, Argyllshire. Anal. F. Coles Phillips (p. 251).

VIII. Greenish-brown biotite, Hill of Strone, Forfarshire. Anal. W. H. Herdsman (p. 252).

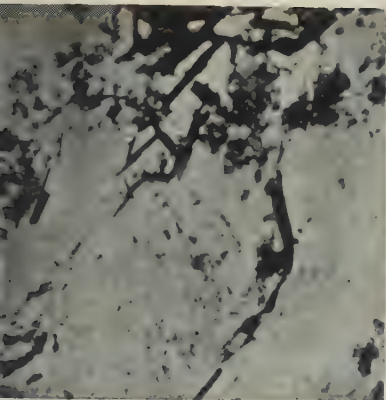
IX. Garnet, Dalnacarn Craig, near the Kirkmichael road, five miles NE. of Pitlochry, Perthshire. Anal. W. H. Herdsman (p. 252).

EXPLANATION OF PLATE X.

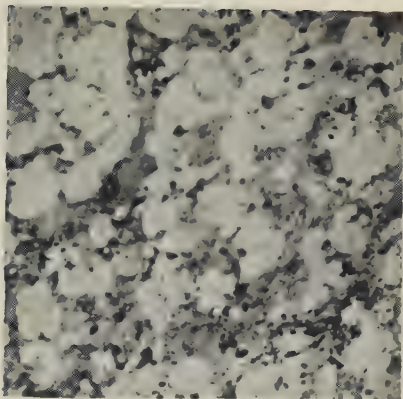
- FIG. 1. Biotite-epidote-albite-schist, Ballochandrian, Cowal, Argyllshire; from the chlorite zone. Elongated crystals of greenish-brown mica, granular epidote, and cloudy albite porphyroblasts. The clear areas are quartz.
- FIG. 2. Chlorite-albite-schist, Glen Fyne, Argyllshire; from the chlorite zone. Abundant albite in a ground of chlorite and iron-ores.
- FIG. 3. Chlorite-epidote-albite-schist, Balquhidder, Perthshire; from the biotite zone.
- FIG. 4. Garnetiferous biotite-epidote-albite-schist, Pittiely Burn, ESE. of Aberfeldy, Perthshire; from the garnet zone. Lath-shaped sections of normal-reddish-brown biotite.
- FIG. 5. Garnetiferous hornblende-biotite-plagioclase-schist, Hill of Strone, Forfarshire; from the kyanite zone.
- FIG. 6. Garnetiferous hornblende-plagioclase-schist, south of Caddam, Glen Clova, Forfarshire. A pebbly variety; the clear area is a portion of a lenticular patch of recrystallized quartz.

Magnification in each case $\times 28$. Note the general increase in coarseness of crystallization towards higher grades.

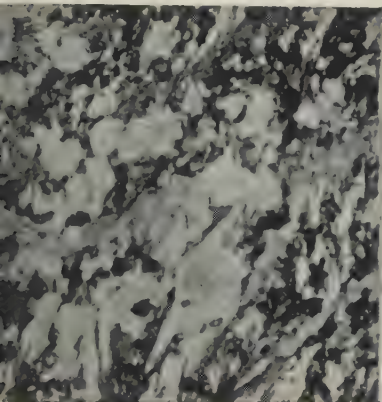
Department of Mineralogy,
Cambridge, November, 1929.



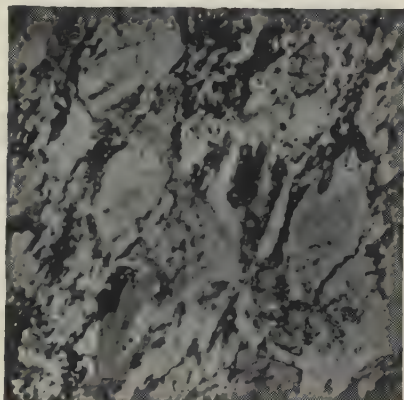
1



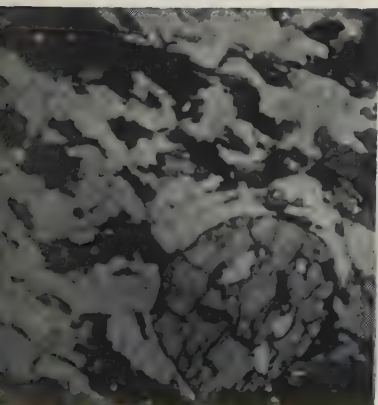
2



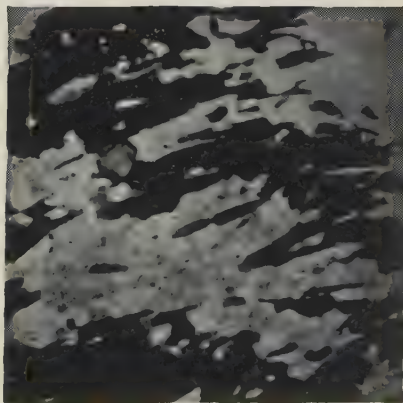
3



4



5



6

Notes on British barytes.

By JESSIE M. SWEET, B.Sc.

Mineral Department, British Museum of Natural History.

[Read June 3, 1930.]

WHEN the slip catalogue of the barytes specimens in the British Museum collection was in the course of preparation, a few observations were made which may be of sufficient importance to place on record.

The lists of localities of the barium minerals, barytes, witherite, alstonite, and barytocalcite, in the collection show that rather more than half of the specimens (573 out of 975) come from the British Isles. Hence it would seem that there is a special concentration of these minerals in this part of the world. Possibly this is fictitious, as the collection cannot be considered to be completely representative. Nevertheless, it is evident from statistics that Great Britain, for its area, is one of the chief commercial producers. This may be illustrated by the figures given below showing the production of barium minerals for 1913 and 1926¹ in some of the leading countries.

	Year 1913.	Year 1926.
United States of America	40,445	212,388 long tons.
Germany	155,525	178,522
Great Britain	50,045	42,775
France	12,039	38,197
Italy	12,762	31,342
Spain	2,999	7,137
Belgium	11,807	6,004

Two concentrations of barium minerals in Great Britain are of especial interest, namely those in the north of England and in Derbyshire. Barium minerals have been known in these districts for many years, but in the days when lead and zinc mining flourished they were considered merely as waste products as was also the fluorite from neighbouring localities. It has been thought for some time that the

¹ Imp. Min. Res. Bureau, Statistical Summary, London, 1921 and 1929.

modes of origin of these two minerals are closely related, especially as in both areas they are associated with basic igneous rocks.

The rocks of the north of England belong to the Carboniferous System, and into these the Whin Sill and its related dikes have been intruded. The geological structure of the area is represented diagrammatically in the E.-W. section in fig. 3*a*, showing that the whole region forms a syncline. Dr. J. A. Smythe¹ has already pointed out that the barytes localities form a ring following the outcrop of the Whin Sill, while the fluorite localities are concentrated in the centre of the area. This fact is clearly brought out in the accompanying map (fig. 1). Specimens showing both fluorite and barytes in close association are exceptional, as may be gathered by reference to the detailed lists of localities on pp. 261-4.

The other area under consideration is in Derbyshire, where there appears to be a similar intimate connexion between barytes and fluorite and the local igneous rocks. Central Derbyshire is composed of Carboniferous Limestone with interbedded toadstones. These have an anticlinal structure with a roughly elliptical outcrop (fig. 3*b*). The deposits form part of a ring round the igneous area, which is cut off on the west by a series of faults. In this instance the barium localities lie within the fluorite localities² (fig. 2), which is the reverse of the conditions in the north of England.

The reason for this definite arrangement in the distribution of these minerals is an interesting problem, and the following is offered as a possible explanation. At the time of formation of the lodes, juices or vapours given off by the molten magma penetrated along fissures in the surrounding rocks. The heavy minerals, such as barytes, were deposited first, while the more volatile fluorine compounds, by their action on the limestones, deposited fluorite higher up in the veins. This was followed by the folding and subsequent denudation of the area. In a synclinal area, as in the north of England, the barytes would then surround the fluorite; whereas in an anticlinal area, as in Derbyshire, the fluorite would be outside the deposits of barytes.

One would expect to find in these rocks an appreciable amount of barium compounds, but the detailed analyses of Dr. H. F. Harwood³

¹ J. A. Smythe, *Minerals of the North Country*. The Vasculum, Newcastle-upon-Tyne, 1922, vol. 8, p. 91. [Min. Abstr., vol. 3, p. 24.]

² Mem. Geol. Survey, Special Reports on the Mineral Resources of Great Britain, Barytes and witherite, 3rd edition, 1922, vol. 2, p. 64.

³ A. Holmes and H. F. Harwood, *Min. Mag.*, 1928, vol. 21, p. 530.

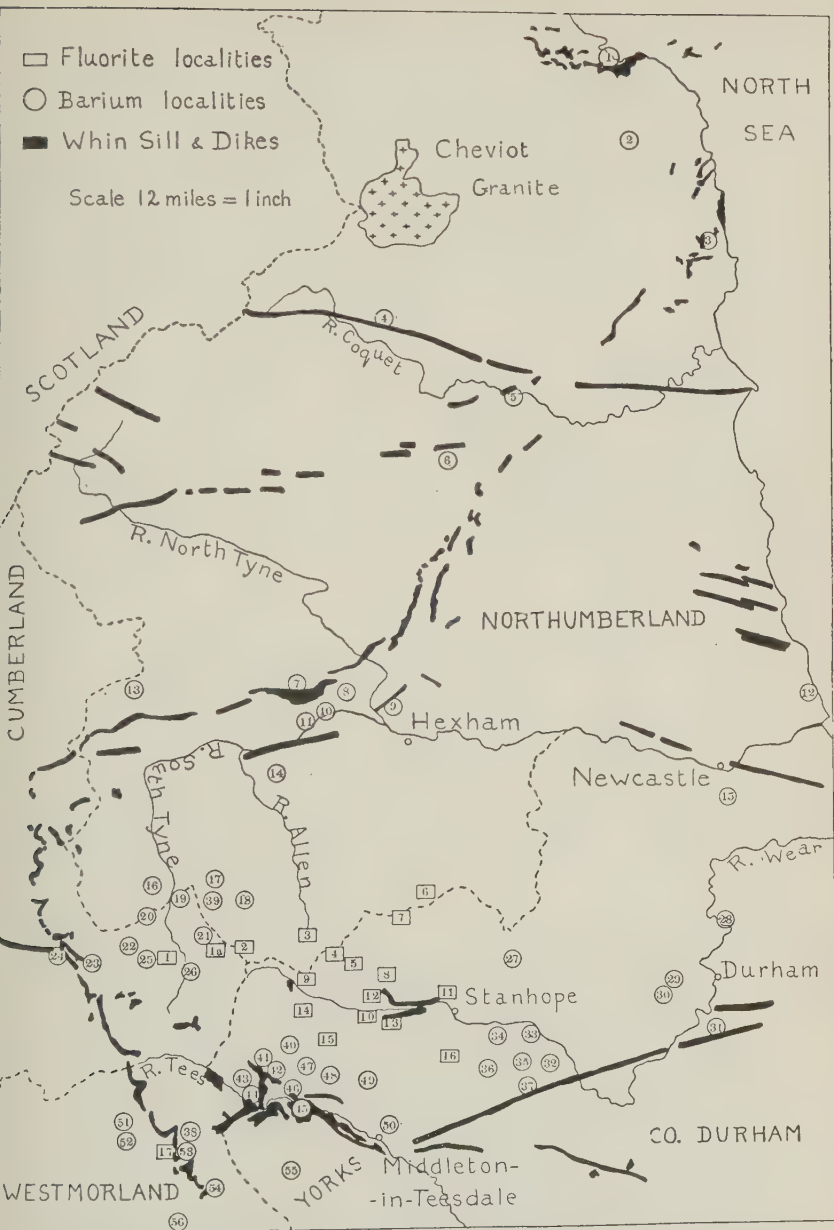


FIG. 1. Map of the north of England showing the distribution of barytes and fluorite localities (pp. 261-3) in relation to the outcrop of the Whin Sill and dikes.

of the Whin Sill show an average of only 0.03% BaO, as against an average of 0.079% deduced by F. W. Clarke and H. S. Washington¹ for the whole of the earth's crust. This lower percentage may

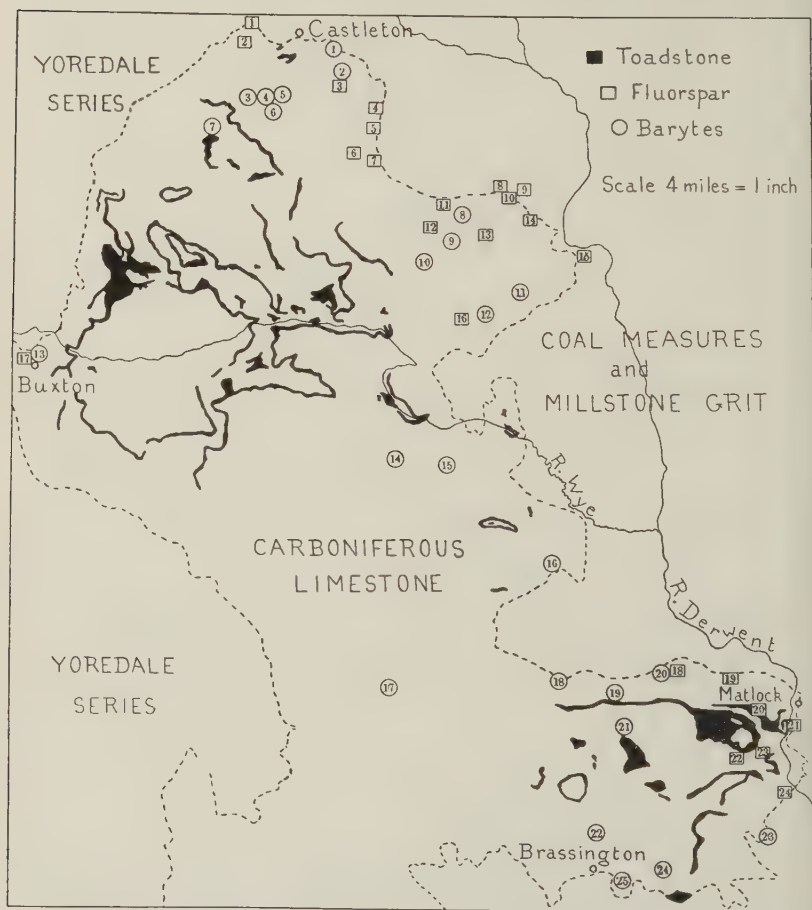


FIG. 2. Map of central Derbyshire showing the distribution of barytes and fluorite localities (pp. 263-4) in relation to the outcrop of the toadstones.

possibly be due to the fact that the barium compounds have already been to a large extent extracted.

To make the maps (figs. 1 and 2) as detailed as possible, lists of localities of barium minerals and fluorite have been culled from

¹ Min. Abstr., vol. 2, p. 60.

various sources. The resulting lists are given below, together with a reference to the authority for each locality. The first source made use of is the British Museum topographical lists, for specimens that are definitely localized, other than merely labelled 'Derbyshire', 'Matlock', 'Cumberland', 'Alston', &c. (these are referred to as 'B.M.'). Then the Memoirs of the Geological Survey, Special Reports on Mineral Resources of Great Britain,¹ were consulted for further localities not represented in the British Museum collection (marked in the lists 'G.S.'); thirdly, the papers by Dr. J. A. Smythe,

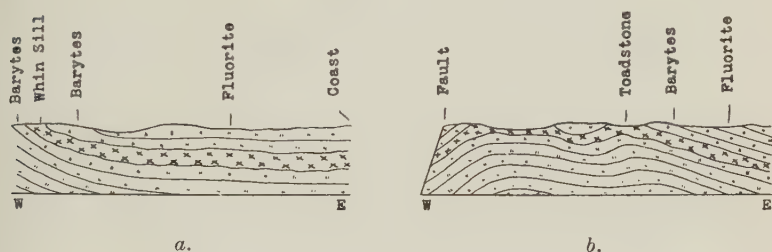


FIG. 3. Diagrammatic geological sections across

(a) the north of England syncline; (b) the central Derbyshire anticline.

'Minerals of the North Country'² ('J. A. S.'), which is likewise exclusive of the first two; and finally R. P. Greg and W. G. Lettsom, *Mineralogy of Great Britain and Ireland*, 1858 ('G. & L.'). Each locality is given a number by which it is represented on the corresponding map. These numbers run approximately from north to south and west to east.

List of Barium localities in the Whin Sill area of the North of England.

(Including the species barytes, witherite, alstonite, and barytocalcite.)

1. Budle Bay, Belford, Northumberland. (J.A.S.)
2. Burton, Belford, Northumberland. (G. & L.)
3. Howick, Alnwick, Northumberland. (J.A.S.)
4. Barrow Scroggs, Alwinton, Northumberland. (J.A.S.)
5. Whitton Dene, Rothbury, Northumberland. (J.A.S.)
6. Redpath, Fallowlees Burn, Northumberland. (J.A.S.)
7. Tepper Moor, Fourstones, Hexham, Northumberland. (G.S.)

¹ 3rd edition, 1922, vol. 2 (Barytes and witherite); 2nd edition, 1917, vol. 4 (Fluorspar).

² J. A. Smythe, *The Vasculum*, Newcastle-upon-Tyne, 1922, vol. 8, pp. 90, 113 and 1927, vol. 14, pp. 15, 16.

8. Walwick Fell, Fourstones, Hexham, Northumberland. (G.S.)
9. Fallowfield mine, Hexham, Northumberland. (B.M.)
10. Stonecroft, Fourstones, Hexham, Northumberland. (B.M.)
11. Settlingstones mine, Fourstones, Hexham, Northumberland. (B.M.)
12. Marden, Cullercoats, Tynemouth, Northumberland. (J.A.S.)
13. Thirlwall Common, Greenhead, Haltwhistle, Northumberland. (J.A.S.)
14. Langley Barony mine, Haydon Bridge, Hexham, Northumberland. (B.M.)
15. Felling, Gateshead, Co. Durham. (J.A.S.)
16. Ayle Burn mine, Ayle, Northumberland. (B.M.)
17. Mohope Head, West Allendale, Northumberland. (B.M.)
18. Carrshield low level mine, West Allendale, Northumberland. (B.M.)
19. Blagill mine, Alston, Cumberland. (B.M.)
20. Park mines, Alston, Cumberland. (G.S.)
21. { Nentsbury mine, Nenthead, Alston, Cumberland. (B.M.)
 { Brownley Hill mine, Nenthead, Alston, Cumberland. (B.M.)
22. Scarberry Hill, Alston, Cumberland. (G.S.)
23. Hartside mine, Alston, Cumberland. (G.S.)
24. Long Cleugh, West Allendale, Northumberland. (B.M.)
25. Rotherhope mine, Alston, Cumberland. (G. & L.)
26. Crag Green, Garrigill, Alston, Cumberland. (G.S.)
27. Burnhill, Waskerley, Wolsingham, Co. Durham. (G.S.)
28. Lumley colliery, Durham, Co. Durham. (G.S.)
29. Ushaw Moor colliery, Durham, Co. Durham. (B.M.)
30. New Brancepeth colliery, Durham, Co. Durham. (B.M.)
31. Croxdale colliery, Durham, Co. Durham. (G.S.)
32. { Black Band Plant Wood, Wolsingham, Co. Durham. (G.S.)
 { Knitsley Fell mine, Wolsingham, Co. Durham. (G.S.)
33. Wiserley, Wolsingham, Co. Durham. (G.S.)
34. Sunnyside Allotment, Wolsingham, Co. Durham. (G.S.)
35. { Harthope Hill, Wolsingham, Co. Durham. (G.S.)
 { Cabin Hill, Pikestone Moor, Wolsingham, Co. Durham. (G.S.)
36. North Grain Beck, Wolsingham, Co. Durham. (G.S.)
37. Black Hill Top mine, Hamsterley, Wolsingham, Co. Durham. (G.S.)
38. Murton Fell, Appleby, Westmorland. (B.M.)
39. Wellhope, West Allendale, Northumberland. (G.S.)
40. Highfield Hushes, St. John's Chapel, Co. Durham. (G.S.)
41. Willy Hole mine, Harwood Fell, St. John's Chapel, Co. Durham. (G.S.)
42. Grasshill Common, St. John's Chapel, Co. Durham. (G.S.)
43. Greenhurth mine, Harwood Fell, St. John's Chapel, Co. Durham. (G.S.)
44. Dubby Sike mine, Harwood Fell, St. John's Chapel, Co. Durham. (G.S.)
45. Widdy Bank Fell, Middleton-in-Teesdale, Co. Durham. (G.S.)
46. Cow Green mines, Harwood Fell, St. John's Chapel, Co. Durham. (G.S.)
47. Bands mine, Langdon Fell, St. John's Chapel, Co. Durham. (G.S.)
48. Ettersgill mines, St. John's Chapel, Co. Durham. (G.S.)
49. Flushiemere mine, Middleton-in-Teesdale, Co. Durham. (G.S.)
50. Snaigill mine, Middleton-in-Teesdale, Co. Durham. (G.S.)
51. Silverband mine, Dufton, Appleby, Westmorland. (B.M.)
52. Dufton Fell mines, Dufton, Appleby, Westmorland. (G.S.)
53. Scordale mines, Hilton, Appleby, Westmorland. (B.M.)
54. Long Fell mine, Warcop, Appleby, Westmorland. (B.M.)

55. Lunehead mines, Lunedale, North Riding, Yorkshire. (G.S.)

56. Hayber Gill, Warcop, Appleby, Westmorland. (J.A.S.)

List of Fluorite localities in the Whin Sill area of the North of England.

1. Rotherhope mine, Alston, Cumberland. (G.S.)
- 1a. Brownley Hill mine, Nenthead, Alston, Cumberland.¹
2. Killhope mine, Heathery Cleugh, Weardale, Co. Durham. (B.M.)
3. Allenheads, East Allendale, Northumberland. (B.M.)
4. Groverake mine, Rookhope, Weardale, Co. Durham. (G.S.)
5. Wolfcleugh mine, Rookhope, Weardale, Co. Durham. (G.S.)
6. Derwent mines, Hunstanworth, Co. Durham. (B.M.)
7. Bolt's Burn mine, Hunstanworth, Co. Durham. (J.A.S.)
8. { Stotfield Burn mine, Rookhope, Weardale, Co. Durham. (G.S.)
 { Boltsburn mine, Rookhope, Weardale, Co. Durham. (B.M.)
9. Sedling mine, Cowshill, Weardale, Co. Durham. (B.M.)
10. { Cumnock Isle mine, Eastgate, Weardale, Co. Durham. (G.S.)
 { Rigg mine, Westgate, Weardale, Co. Durham. (G.S.)
11. { Stanhope Burn mine, Stanhope, Co. Durham. (B.M.)
 { Crawley Spar mine, Stanhope, Co. Durham. (G.S.)
 { Hope level, Stanhope, Co. Durham. (G.S.)
12. Heights mine, Westgate, Weardale, Co. Durham. (B.M.)
13. Billing Hills mine, Eastgate, Weardale, Co. Durham. (G.S.)
14. Barbary mine, Ireshopeburn, Weardale, Co. Durham. (G.S.)
15. Greenlaws mine, Daddrv Shield, St. John's Chapel, Co. Durham. (B.M.)
16. Yew tree mine, Bollihope Burn, Stanhope, Co. Durham. (G.S.)
17. Scordale mines, Hilton, Appleby, Westmorland. (B.M.)

List of Barytes localities in Central Derbyshire.

1. Pindale, Castleton. (G.S.)
2. Hall mine, Castleton. (G.S.)
3. Portaway mine, Castleton. (G.S.)
4. Hazard mine, Castleton. (G.S.)
5. Holland Twine mine, Castleton. (G.S.)
6. Old Moor mine, Castleton. (G.S.)
7. Oxlow End, Castleton. (G.S.)
8. Foolow, Tideswell. (G.S.)
9. Dirty Rake, Middleton Moor, Tideswell. (G.S.)
10. White Rake, Wardlow, Tideswell. (G.S.)
11. Sallet Hole mine, Combs Dale, Stony Middleton. (G.S.)
12. Longstone Edge, Great Longstone. (G.S.)
13. Buxton. (G. & L.)
14. Magpie mines, Sheldon, Bakewell. (G.S.)
15. Magshaw Rake, Sheldon, Bakewell. (G.S.)
16. Alport, Youlgreave. (G.S.)
17. Newhaven, Youlgreave. (B.M.)
18. Elton, Winster. (G.S.)
19. Winster. (G.S.)

¹ Collected by Dr. L. J. Spencer, 1909.

20. Mill Close mine, Wensley, Darley Dale, Matlock. (B.M.)
21. Bonsall Moor, Winster. (G.S.)
22. Westerhead, Longcliff, Brassington. (G.S.)
23. Bradwell mines, Middleton Cross, Wirksworth. (G.S.)
24. Golconda mine, Griff Grange, Wirksworth. (G.S.)
25. Great Rake mine, Brassington. (G.S.)

List of Fluorite localities in Central Derbyshire.

1. Odin mine, Castleton. (G.S.)
2. Blue John mine, Treak Cliff, Castleton. (B.M.)
3. Smalldale Head, Bradwell, Castleton. (G.S.)
4. Hill Rake, Bradwell Dale, Castleton. (G.S.)
5. Hazlebadge Hall, Bradwell Dale, Castleton. (G.S.)
6. Intake Dale mine, Bradwell, Castleton. (G.S.)
7. Netherwater, Bradwell, Castleton. (G.S.)
8. Broadlow mine, Eyam. (G.S.)
9. Ladywash mine, Eyam. (G.S.)
10. Pasture mine, Eyam. (G.S.)
11. Waterfall mine, Foolow, Tideswell. (G.S.)
12. Stanley Moor, Tideswell. (G.S.)
13. Needham's Hanging Flat mine, Eyam. (B.M.)
14. Glebe mine, Eyam. (G.S.)
15. Calver mine, Stony Middleton, Bakewell. (G.S.)
16. Longstone Edge, Great Longstone. (B.M.)
17. Buxton. (B.M.)
18. Mill Close mine, Wensley, Darley Dale, Matlock. (B.M.)
19. Ox-close Pipe, Snitterton, Matlock. (G.S.)
20. High Loft (= Knowles) mine, Masson Hill, Matlock. (G.S.)
21. Long Tor, Matlock. (B.M.)
22. Stubbin (= Low) mine, Bonsall, Matlock. (G.S.)
23. Hopping Pipe mine, Matlock Bath. (B.M.)
24. Mole-trap Lode, Cromford. (G.S.)

Having given some account of the distribution of barytes, it may be interesting to examine a few of the British specimens, which vary considerably both in colour and habit. White opaque crystals (including botryoidal and plumose forms) come from Shropshire; Staffordshire; Derbyshire; the Lake District; Settlingstones mine, Northumberland; Nentsbury mine, Cumberland; New Brancepeth colliery, Co. Durham; Wanlockhead, Dumfriesshire, &c. Clear colourless crystals are found chiefly at Silverband mine, Dufton, Westmorland, and Wotherton mine, Chirbury, Shropshire. The Cornish specimens are generally either honey-yellow or greenish-grey, while pinkish lamellar crystals are found at Babbacombe Bay, Devonshire, and Nether Stowey, Somerset. A deep chocolate-brown, stalactitic variety comes from Newhaven, Derbyshire. But the most

beautiful specimens in the collection are those from the west Cumberland iron mines, and it is these that will now be considered in greater detail. They occur in deposits that have no genetic relation with those considered above in the Whin Sill area some fifty miles to the east, and for this reason these localities are not included in the list on pp. 261-3.

The crystals from the Dalmellington and Parkside mines at Frizington¹ vary in colour from a clear pale-yellow to a rich chocolate-brown and may have either a tabular or prismatic habit. The variation in colour is due to inclusions of haematite and iron hydroxides, which sometimes permeate the entire crystal, but in other cases they occur just beneath the surface and are distributed along certain faces only.

The crystals from Mowbray mine, Frizington, are varied in colour. They range from colourless, pale-yellow and yellow-brown through many shades of greenish-blue and greenish-yellow to sky-blue. They are usually tabular in habit. An interesting yellowish-green curved crystal in the British Museum collection has been described by Dr. Spencer.² This curvature is due to a sub-parallel grouping of individual crystals. Some of the crystals from this mine show an interesting colour-change, which has not been previously recorded. There are, in the collection, several specimens which were bought from Mr. J. Graves of Frizington in 1909 and 1913. Entries in the Museum Register show that at the time of purchase these specimens were pale-yellow or amber-yellow in colour, whereas, when the slip-catalogue was made in 1928, their colours varied from pale-green to sky-blue. Dr. Spencer kindly provided pale-yellow crystals, which he had collected in 1909 and had since kept in the dark. One specimen was exposed to bright sunlight at 10.30 a.m. on June 25, 1928, and another kept in the dark for comparison. The exposed crystal was kept under close observation. At 12 noon there was no appreciable change, but at 2.15 p.m. the entire crystal had become pale greenish in colour and at 4.20 p.m. it was observed to be distinctly blue-green. The specimen was kept in the window for some time, and by July 2 it had become completely blue.

No explanation can be offered to account for this striking change in colour in barytes. Though yellow crystals from Cumberland are

¹ These mines are situated close to the Frizington railway station and are now amalgamated.

² L. J. Spencer, *Min. Mag.*, 1921, vol. 19, p. 266, and pl. 8, fig. 11.

common, it is only those from Mowbray mine that exhibit this peculiarity. Many examples are known of the changes in colour of minerals when exposed to light, the emanations of radium, or to changes in temperature.¹ But in only a few cases can any satisfactory explanation be given. The striking change undergone by cerargyrite and the silver halides, on which indeed the whole process of photography is based, is of course well known. Other examples which may be mentioned here are the changes in colour of certain fluorites. The miners in Weardale expose specimens to the sunlight for the express purpose of 'improving the colour', thus effecting a change from green to purple. The purple fluorite, on heating, becomes completely decolorized. Another interesting change in colour by exposure to light has been recently observed in the British Museum collection in the case of a large crystal of topaz from Cairngorm, Banffshire. This crystal, formerly in the collection of Thomas Allan, was figured and described by James Sowerby in 1811.² He says: 'It is the more curious, as part of it is of a fine light blue colour, and part cinnamon-coloured, with a beautiful soft glowing warmth; and the disposition of the two colours seems almost to explain the nature of the crystallization. I thought therefore it would be instructive to give a figure of the base of the crystal, showing nearly the form the colours are disposed in.' This specimen came into the possession of the British Museum in 1860. The cinnamon colour referred to has now completely disappeared, leaving the whole crystal pale blue.

While the subject of colour is being discussed it is interesting to note the variation in distribution of colour in individual crystals. This, of course, is caused by a slight change in composition of the solution from which the barytes crystallized, and it gives rise to very decided zoning effects. Three of the more interesting types of zoning are represented more or less diagrammatically in fig. 4 *a-c*.

(*a*) A tabular crystal (B.M. 61426) from Crowgarth mine, Egremont, zoned in varying shades of yellowish-green. The innermost crystal had the forms *c d m*; as it grew in the direction of the *b*-axis it developed a pair of *o* (011) faces, and these eventually became cut out again by the *m* faces.

(*b*) A tabular crystal (B.M. 1913,406) from Mowbray mine, Friz-

¹ See, for example, the section 'Colour of minerals' in Min. Abstr., vol. 1, p. 227; vol. 2, p. 491; vol. 3, p. 115; vol. 4, p. 251.

² J. Sowerby, British Mineralogy, 1811, vol. 4, p. 117 (tab. 363).

ington, with a deep-yellow centre and pale-yellow edge. It will be observed that during the early stages of growth there was a good development of the b (010) face, but that this was gradually cut out during later stages.

(c) A tabular crystal (B.M. 85620) from Mowbray mine, Frizington, zoned in shades of brown, but showing clear tips. The b (010)

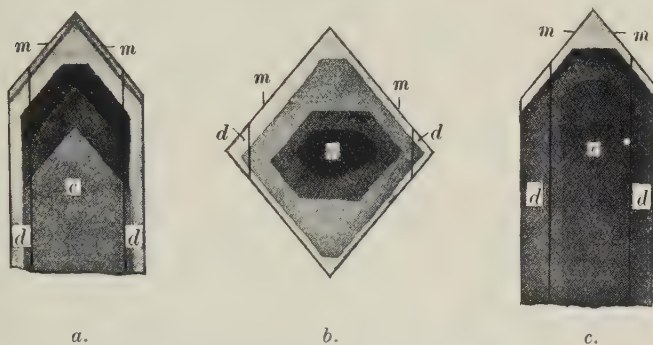


FIG. 4. Zoned crystals of barytes from Frizington, Cumberland, showing the stages of growth marked out by different colours.

face has been cut out during the later stages of growth. This type is of very common occurrence.

From observations on these banded crystals it seemed probable that some idea of the relative rate of growth normal to the crystal faces might be determined. Approximate measurements of the width of the bands parallel to the m and b faces were made on eleven different crystals. In eight of these crystals the ratio b/m varied from 1–1.5 (where b = growth normal to the b face and m = growth normal to the m face). Three other crystals gave much higher values for b/m , viz. 2.1, and two of 2.8. It was observed that in the last cases the b face was becoming rapidly cut out by the m faces. Hence the ratio b/m is not a constant, but varies with the relative rate of growth of the crystal, which in its turn depends on changes in the physical and chemical conditions under which the crystal is growing. Outline drawings were made for the purpose of demonstrating geometrically the effect of changing rates of growth on the sizes of the faces, and it was found that the sizes of the faces depend on their relative rates of growth. Fig. 5a is drawn with $b : m = 1.2 : 1$ (the mean of the measurements on eight crystals), and fig. 5b with $b : m = 2.8 : 1$. The former shows a regular increase in the b face, and is

illustrated by the growth of the dark band in fig. 4c. The latter shows a rapid and regular diminution in the b face, illustrated by the banding in fig. 4b. It follows from this that there must be relative rates of growth of the b and m faces for which the size of the b face remains constant. Such a condition is represented in fig. 5c, where the lines joining the ends of the b faces are parallel. Here the ratio b/m is 1.583, as given by $\text{cosec } \theta$, where θ is half the barytes angle $mm = 78^\circ 22\frac{1}{2}'$.

Another interesting feature of the west Cumberland crystals is a

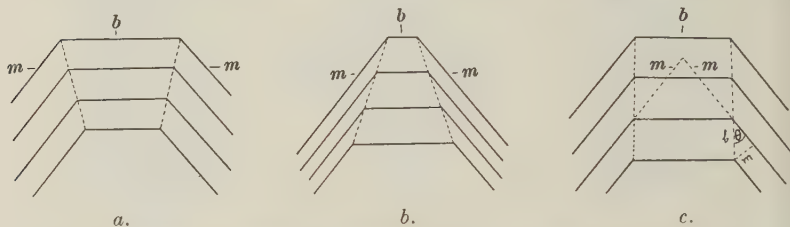


FIG. 5. Diagrams of crystals showing the effect of a varying relative rate of growth on the size of the $b(010)$ face.

(a) $b:m = 1.2:1$. (b) $b:m = 2.8:1$. (c) $b:m = 1.6:1$.

rich development of lines of growth on the various faces. Fig. 6 is an attempt to represent those seen on a crystal (B.M. 1907,384) from Dalmellington mine, Frizington, but it is almost impossible to reproduce the minute delicacy of the surface markings. On the $c(001)$ faces the striations often show a simple 'herring bone' pattern parallel to the $m(110)$ faces with a suture approximately parallel to $a(100)$. Often there are also other sutures at right angles to the first, on the other side of which the striations slope in the opposite direction, thus forming rhomb-shaped figures or very low pyramids of growth. Other markings suggestive of 'terraces of growth' are bounded by striations parallel to the $a(100)$ faces as well as the $m(110)$ faces.

A considerable number of crystal-forms are represented on the west Cumberland specimens, but as the crystals are usually too large for goniometric measurement and the faces often uneven, a detailed study of these has been deferred. The common forms, determined with the contact-goniometer, are $c(001)$, $d(102)$, $m(110)$, $o(011)$, and $z(111)$,¹ and these are present on almost every crystal. Special atten-

¹ Letters and indices as in Dana (1892) with the axial ratios $a:b:c = 0.8152:1:1.3136$ of R. Helmhacker (1872).

tion must, however, be drawn to two unusual forms occurring on crystals from Parkside and Dalmellington mines at Frizington. In habit these crystals are prismatic in the direction of the b -axis, and they show faces with the form of acute scalene triangles placed at the corners between d (102) and m (110), but not lying in any prominent zone on the crystal. These faces are usually small and are always furrowed and grooved, giving no sharp reflection on the goniometer. They are evidently forms developed during the growth of the crystal and on larger specimens tend to become eliminated. In most cases these faces are striated parallel to their intersection with d (102) as indicated in fig. 7, but sometimes they show wavy oscillations in the zone between u (101) and z (111) (fig. 6).

Forms of this character with the indices π (916), n (718), l (14.2.9), X (15.3.10), δ (414), b (28.7.24), t (11.3.6), ω (313), γ (312), (15.5.12), &c., have been previously recorded from other localities, but apparently not from Cumberland. Amongst the 737 figures of barytes copied in V. Goldschmidt's 'Atlas der Krystallformen' (vol. 1, 1913) fourteen show faces of this character, the localities being Saxony, Hungary, Bohemia, Scotland, and Norway. In the British Museum collection thirteen specimens from Dalmellington and Parkside mines, Frizington; two from Pallaflat mine, Egremont; two from Příbram, Bohemia; and one from Marienberg, Saxony, show faces of this description. Fig. 7 *a* represents a crystal (B.M. 1907,383) from Dalmellington mine, 10 cm. in length with only a small point of attachment and equally developed on all sides, all eight faces of the (hkl) form being present. Approximate measurements with the contact-goniometer suggest the form t (28.7.24). Fig. 7 *b* represents a crystal (B.M. 1907,391) from Parkside mine, small enough for measurement on the reflecting goniometer, but the pyramid faces gave only blurred reflections of the signal. These seem to be nearer the form l (14.2.9). The directions of the somewhat rounded edges in the plane (001) were measured under the microscope. On the next page are given the observed and calculated measurements:

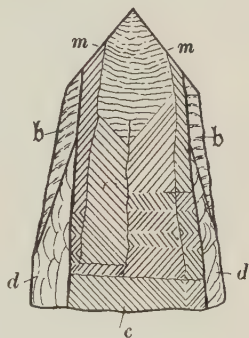


FIG. 6. Sketch illustrating the lines of growth on the faces of a crystal of barytes from Frizington, Cumberland.

	Obs.	Calc. (R. Helmhacker, 1872.)
$h(28.7.24) : h(28.7.\bar{2}4) \dots \dots \dots$	54°	$55^\circ 4'$
Edge $[(28.7.24), (28.7.\bar{2}4)] : [(100), (001)]$	11	11 31
$l(14.2.9) : c(001) \dots \dots \dots$	$67\frac{1}{2}$	68 23
Edge $[(14.2.9), (14.2.\bar{9})] : [(100), (001)] \dots$	$6\frac{1}{2}$	6 39

The form $h(28.7.24)$ was first observed by R. Helmhacker in 1872¹ on crystals from Dědova Hora (Giftberg) and Krušná Hora, Bohemia, and the form $l(14.2.9)$ by A. Lévy² in 1837, from Freiberg, Saxony.

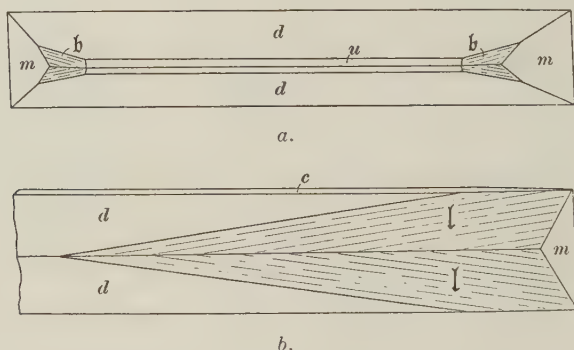


FIG. 7. Crystals of barytes from Frizington, Cumberland, showing the development of acute pyramids with high indices.

In spite of the wealth of material no detailed account of the barytes crystals from the west Cumberland iron mines has ever been attempted. In V. Goldschmidt's 'Atlas' not a single crystal represented is stated to be from this district.³

In conclusion I should like to thank Dr. L. J. Spencer for suggesting this subject, and for his encouragement and help throughout, especially in the determination and drawing of the crystal-forms. I am also indebted to Mr. M. H. Hey for suggestions relating to crystal-growth.

¹ R. Helmhacker, Denkschr. Akad. Wiss. Wien, 1872. vol. 32, part 2, pp. 34, 36, and pl. 2, figs. 15, 17, 21.

² A. Lévy, Description d'une collection de minéraux formée par M. H. Heuland 1837, vol. 1, p. 200, no. 69, and pl. 16, fig. 14.

³ A crystal from 'Cumberland' figured by F. J. Wiik, Öfv. Finska Vet. Soc. Förh., 1884, vol. 26 (for 1883-4), p. 112, fig. 1, is possibly from the Frizington district. The figure shows curved lines of growth on the $d(102)$ faces.

*A new meteoric iron from Piedade do Bagre,
Minas Geraes, Brazil.*

(With Plates XI and XII.)

By L. J. SPENCER, M.A., Sc.D., F.R.S.

With a chemical analysis by M. H. HEY, B.A., B.Sc.
Mineral Department, British Museum of Natural History.

[Read June 3, 1930.]

A MASS of iron weighing 130 lb., stated to have been found in 1922 near the village of Piedade do Bagre in Minas Geraes, Brazil, and believed to be meteoric, was submitted by Mr. N. Medawar in January 1929 to the Mineral Department of the British Museum for examination. The following description of the mass fully confirms the supposition of its meteoric origin. Unfortunately, only scanty details are available of the circumstances of the finding of the mass. All the information that Mr. Medawar was able to supply is given in the following short note written by Mr. R. J. Bohrer, with a rough sketch-map of the locality.

Meteorito encontrado no ponto marcado +. Vendido por intermedio do Snr. Padre José Alves de Curvello a Rodolpho J. Bohrer. Encontrado em 1922 por um situante cujo nome não se conhece. Vendido a Snr. Medawar em Março de 1927.

Mr. Medawar's translation of this is:

Meteorite found at the point marked +. Sold by the intermediary of Mr. Padre José Alves of Curvello to Rodolpho J. Bohrer. Found in 1922 by a local native whose name not known. Sold to Mr. Medawar in March of 1927.

The spot marked is about 16 km. (10 miles) SW. of the village of Piedade do Bagre in Minas Geraes. This village is situated between the Rio São Francisco and the Rio das Velhas, and is about 155 km. NW. of Bello Horizonte, the capital of Minas Geraes, and about 155 km. WSW. of Diamantina. It is about 50 km. west by south of the railway station of Curvello and about 33 km. east of the railway

station of Paraopéba.¹ The district of Piedade do Bagre is in the município of Curvello, but it is probable that the meteorite was found just over the boundary in the adjoining município of Pitanguy. As near as can be determined, the position of the find is given by lat. $18^{\circ} 56\frac{1}{2}'$ S., long. $44^{\circ} 59'$ W. The position is indicated by a cross on the accompanying sketch-map (fig. 1), which is a tracing from the Brazilian sheets dated 1922 of the International Map of the World on a scale of 1:1,000,000.

When received at the Museum the mass was first weighed and measured. The weight was 130 lb. (= 59 kg.) and the maximum dimensions in three directions at right angles were $39.7 \times 32.1 \times 17.2$ cm. (= $15\frac{5}{8} \times 12\frac{5}{8} \times 6\frac{3}{4}$ inches). It was then photographed by the Museum photographer, Mr. H. G. Herring, and coloured plaster casts were made by Mr. P. Stammwitz, preparator in the Department of Zoology. With Mr. Medawar's approval an end-piece was then sawn off, and from this a corner weighing 19 grams was cut off for chemical analysis. After smoothing and polishing the two cut surfaces, the end-piece weighed $2127\frac{1}{2}$ grams. This piece (pl. XII, fig. 7) was generously presented to the Museum by Mr. Medawar. Sawdust and filings weighed about 100 grams, leaving the main mass at 125 lb.

The general shape of the mass, which is represented from three points of view in figs. 2 and 3, and fig. 5 of pl. XI, calls for no special remark. There are broad concave surfaces, but no smaller well-marked pits. The surface is weathered and a small amount of scale was detached in the process of cleaning. Portions of this scale are magnetic and attract the filings from the mass. The complex of broad and shallow concave surfaces shown by most iron meteorites would appear to be the result of atmospheric weathering.²

¹ Another place called Paraopéba, the chief town of the município of the same name, is situated 62 km. south of Curvello.

² The same character of surface is shown by the gigantic meteoric iron at Hoba in South-West Africa, on the Hoba West farm, 12 miles west of Grootfontein [Min. Abstr., vol. 4, p. 261]. Here the mass is surrounded by a thick layer of scale, which has obviously been formed by the weathering of the iron. This 'iron shale' is well exposed in the sides of the pit that has been dug partly round the mass. It has a thickness of one foot and shows a lamination parallel to the adjacent surface of the unaltered iron from which it is sharply separated. The scale is dark-brown to black with a dark-brown streak and it is slightly magnetic. It shows green nickel stains and is seamed with calcium carbonate from the surrounding surface limestone (Kalahari Kalk) in which the mass is embedded. The meteorite has the form of a roughly rectangular block with its large upper surface level with the surrounding ground. A dozen people can

A feature of special interest is the natural octahedral fracture shown on the prominent corner of the mass (upper right-hand corner in fig. 2, and to the right in fig. 5). The crack shown on the shoulder in fig. 2 is parallel to this fractured surface. On this surface there are lines of fissure in three directions at 60° bringing out the octahedral structure of the iron (fig. 6). The elongated triangular surface to the left in fig. 6 appears to be an old saw cut. Beneath

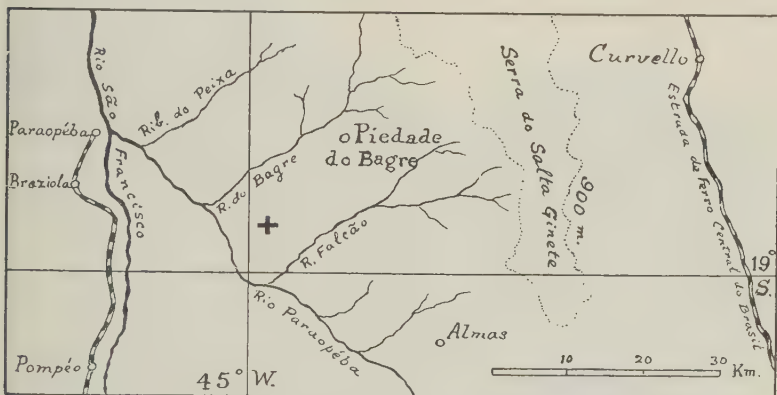


FIG. 1. Sketch-map of locality of the Piedade do Bagre meteorite, Minas Geraes, Brazil. Scale 1:1,000,000.

this is a thin ($\frac{1}{2}$ –1 mm.) pliable plate of metal (kamacite) standing out from the surface. Indications of an octahedral structure are also shown on two flattish surfaces on the mass, one of them showing on the right in the lower right-hand corner of fig. 3.

The plane of section of the end-piece that was cut off the mass was taken more or less parallel (but unfortunately at about 20°) to this octahedral fracture. The polished surface (fig. 7) shows a more or less regular system of cracks parallel to the kamacite bands, again bringing out the octahedral fracture of the iron. This 'cleavage' is a separation along the kamacite lamellae, and not a true crystal

walk about on the level surface of the meteorite. Measurements taken by me in September, 1929, are 295×284 cm. (about 10×9 feet) on the large flat surface, with a thickness at one end of 111–122 cm. and at the other end of 55–75 cm. From these measurements I calculated the weight of the mass to be about 60 metric tons. This considerably exceeds the largest mass (Ahnighito or 'The Tent', $36\frac{1}{2}$ tons) of the Cape York (Greenland) meteoric iron, now in the American Museum of Natural History in New York City, which has hitherto been the record size for a meteorite.

cleavage.¹ This fracturing of the mass was no doubt brought about by the fall of the meteorite on this end on hard rock. The unusually fine development of Neumann lines shown on the etched surface (fig. 8) is also no doubt due to the shock of the impact on this corner of the mass.

Etching with dilute nitric acid gave unsatisfactory results. After



FIG. 2. Photograph of one side of the Piedade do Bagre meteorite, Minas Geraes, Brazil. $\times \frac{1}{4}$.

repolishing the surface it was etched with very dilute bromine water for $1\frac{1}{2}$ hours, which brought out to perfection the Neumann lines. The second small surface was etched for three minutes with a solution of cupric chloride containing an excess of ammonium chloride. On immersion there was immediately a deposition of copper on the surface. This can be readily wiped off the kamacite, but it adheres firmly to the taenite.

The etched surface (fig. 7) shows well-marked Widmanstätten figures, but owing to the low degree of etching they are somewhat

¹ These 'cleavages' in meteoric iron were first observed by W. H. Wollaston in 1816, and have been called 'Wollaston planes' by O. A. Derby, *Archivos do Museu Nacional, Rio de Janeiro, 1896, vol. 9, p. 114.*

faint. The etching was stopped to preserve the fine series of Neumann lines; if it had been carried further to give sharp Widmanstätten figures the Neumann lines may have been obliterated. Possibly this is one reason why Neumann lines have been so rarely observed in octahedrites. In addition to a well-marked triangular arrangement

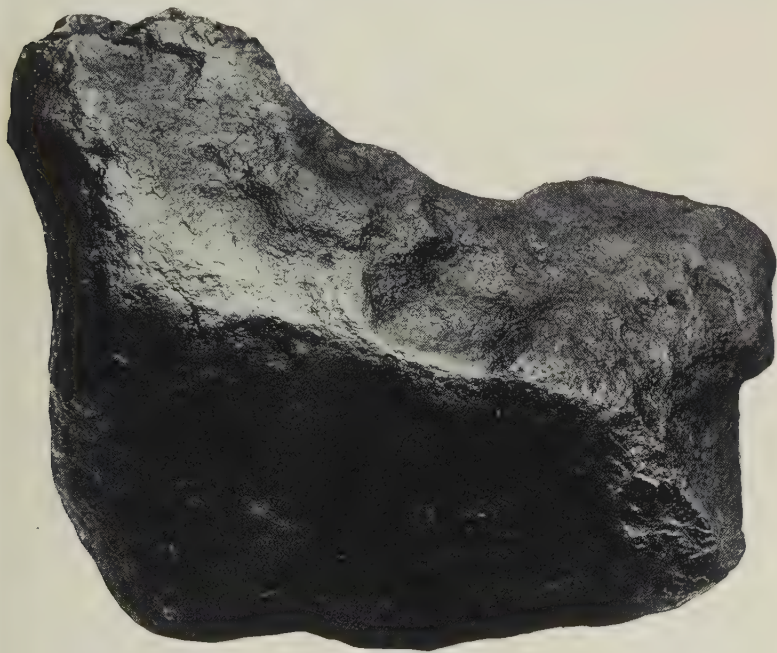


FIG. 3. Photograph of the opposite side of the Piedade do Bagre meteorite. $\times \frac{1}{4}$.

of the kamacite bands, there is a fourth set of broader bands. These broader bands represent the kamacite layers parallel to that face of the octahedron which is inclined at a smaller angle to the section-plane. Measurement of the angles between the kamacite bands could not be made owing to the awkward shape of the specimen. Measurements made on the photographs gave: from fig. 8, 68° , 68° , 44° ; and from fig. 7, 71° , 64° , 45° , and for the fourth set $28^\circ + 43^\circ = 71^\circ$. These are, however, not the true angles, as the surface was not parallel to the photographic plate.¹

¹ N. T. Belaiew, *Crystallisation of metals*. London, 1923, p. 76 [Min. Abstr., vol. 2, p. 87], gives a table of angles showing the relation between the angles of Widmanstätten figures and the orientation of the section-plane. See also J.

In the triangular set the kamacite bands are about 1 mm. wide, so that the iron can be classed as a 'medium octahedrite'. But, as noted above, the width of the bands depends on the direction of the section. Very thin strings of brilliant tin-white taenite border the kamacite bands (fig. 8), and there are well-marked areas of plessite. Troilite is present in small amount as scattered nodules, quite small in size and elongated in shape. Some of them show parallel bands of an included tin-white material, possibly schreibersite. The parallelism of these bands and their abrupt ending at the surface of the troilite suggest that the nodules are corrosion remnants, rather than, say, fused drops. A group of very minute specks of troilite (surrounded by a white stain on the iron) is shown in the upper central part of fig. 7. The minute white spots in some of the kamacite bands (e. g. lower band in fig. 8) are perhaps cohenite.

The smaller etched surface (3×2 cm. shown dark on the left in fig. 7) is nearly parallel to a cube face. On this a rectangular arrangement of the Widmanstätten figures is shown. The copper etching brings the taenite into prominence and minute rods and specks of it are seen throughout the plessite areas. Copper-coloured specks seen under the microscope in the kamacite bands perhaps represent cohenite. Neumann lines were not developed by this etching.

A special feature of the Piedade do Bagre meteorite is the abundance and distinctness of the Neumann lines in the bands of kamacite. In the literature I have not been able to find anything to compare with fig. 8. The lines are readily visible to the unaided eye and are still evident in the slightly reduced photograph (fig. 7), while under a magnification of ten diameters (fig. 8) they are very marked. It will be seen that the lines are confined to the kamacite bands, and that they end abruptly at the narrow strings of taenite.

In parallel bands of the kamacite there is a parallelism of the Neumann lines, but the lines do not always continue in the same straight line across a taenite strip. Further, lines with some directions present in one band may be absent in the next. Under the microscope the lines are seen to be grooves with somewhat jagged edges and a depressed granular surface. An oriented sheen on the etched surface is only slightly evident when the specimen is turned about in reflected light.

Neumann lines are now known to be twin-lamellae produced by Leonhardt, *Neues Jahrb. Min., Abt. A*, 1928, vol. 58, p. 179 [*Min. Abstr.*, vol. 4, p. 122].

gliding on planes of the icositetrahedron $\{211\}$. The traces of these on the faces of the octahedron are represented in fig. 4a, where in each case a plane of $\{211\}$ passes through a corner of the octahedron. On each octahedral face there are nine directions of these lines, making angles of 0° , $20^\circ 10'$, $39^\circ 50'$, 60° , and $80^\circ 10'$ with an edge of the octahedron. The twelve faces of the icositetrahedron which

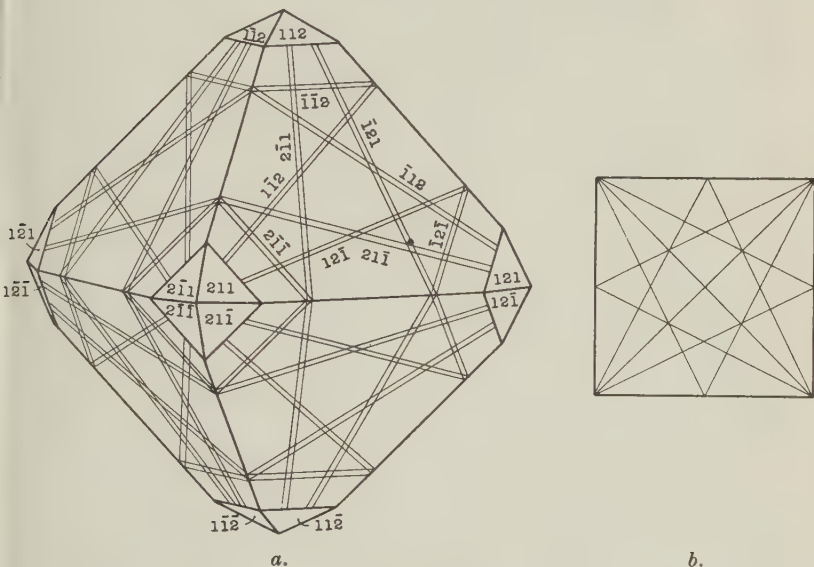


FIG. 4a. Neumann lines. Traces of intersection of planes of the icositetrahedron $\{211\}$ on the faces of the octahedron $\{111\}$. Each face of $\{211\}$ passes through a corner of the octahedron.

FIG. 4b. Intersection of planes of $\{211\}$ on a cube face, giving ten directions for the Neumann lines.

lie in the three zones $[111,211]$, $[111,121]$, and $[111,112]$ account for only three directions of striation on the octahedral face (111); the remaining twelve faces giving rise to the six other directions. Making allowance for the lack of parallelism of the plane of the section with a face of the octahedron, all the directions are represented in fig. 8, though not more than four or five at the same time in any one band of kamacite.

Neumann lines¹ were first distinguished from Widmanstätten

¹ Also called 'Neumann bands' and 'Neumann figures'. The earliest use of the term that I have been able to find is by A. Brezina ('Neumann'schen Figuren') in *Jahrb. Geol. Reichsanst. Wien*, 1885, vol. 35, p. 199.

figures by J. G. Neumann¹ in 1848, during his examination of the Braunau (Bohemia) hexahedral iron. They have been studied by G. Rose (1864), G. Tschermak (1875), A. Sadebeck (1875), O. W. Huntington (1886), O. Mügge (1899), and others, and have been generally thought to be due to a lamellar twinning of the cube on a face of the octahedron or triakisoctahedron {221}. The structure came to be regarded as typical of hexahedrites, which are composed wholly of kamacite without any lamellar intergrowth of taenite to mark out the octahedral structure. Neumann lines have, however, been observed also in the kamacite of octahedral irons. For example, they were described by O. A. Derby² under the name 'Bendigó lines' in the iron of Bendigó (Brazil). Dr. G. T. Prior³ mentioned them in the iron of Vaalburg (South Africa), and recently Sir Harold Carpenter and Dr. S. Tamura⁴ have studied them in the octahedrite of Cañon Diablo (Arizona).

W. Haidinger⁵ in 1855 and G. Linck⁶ in 1892 observed the same structure in artificial iron, and Linck was the first to interpret correctly the several directions of the lines as due to lamellar twinning with gliding on planes of the icositetrahedron (211). Similar lines representing slip-planes due to strain are well known in other metals and have been much studied by metallographers.

An elaborate study of Neumann lines has recently been made by Prof. S. W. J. Smith and his assistants.⁷ They prove that lamellar twinning by shearing is possible on the planes of (211) in a body-centred cubic lattice, which as shown by X-ray analysis is the structure of kamacite and α -iron (taenite and γ -iron having a face-centred cubic lattice). Under high magnification ($\times 1680$) they show many beautiful photographs of Neumann lines and etch-figures on polished surfaces of the Coahuila (Mexico) hexahedrite. The etch-

¹ J. G. Neumann, *Ber. Mitt. Freunden Naturwiss. Wien*, 1848, vol. 4, p. 86. The detailed account appeared later in *Naturwiss. Abhandl. Wien*, 1850, vol. 3, pt. 2, p. 45.

² O. A. Derby, *Archivos do Museu Nacional, Rio de Janeiro*, 1896, vol. 9, p. 153.

³ G. T. Prior, *Min. Mag.*, 1926, vol. 21, p. 189.

⁴ H. C. H. Carpenter and S. Tamura, *Trans. Inst. Mining & Metall. London*, 1928, vol. 37, p. 381, figs. 87-93. [*Min. Abstr.*, vol. 4, p. 239.]

⁵ W. Haidinger, *Sitzungsber. Math.-naturwiss. Cl. Akad. Wiss. Wien*, 1855, vol. 15, p. 354.

⁶ G. Linck, *Zeits. Kryst. Min.*, 1892, vol. 20, p. 209.

⁷ S. W. J. Smith, A. A. Dee, and J. Young, *Proc. Roy. Soc. London, Ser. A.*, 1928, vol. 121, pp. 477-514, 6 pls. [*Min. Abstr.*, vol. 4, p. 121.]

figures inside a band are in reversed orientation to those outside, and when one band crosses another there is a shift (faulting) of the earlier band. These observations prove conclusively that Neumann lines are due to lamellar twinning along glide-planes and that they are of secondary origin and due to strain. They are, in fact, strictly analogous to the secondary twin-lamellae in the grains of calcite in a crystalline limestone that has been subjected to pressure.

The suggestion has already been made by Sir Harold Carpenter (*loc. cit.*) and others that Neumann lines have been developed in the kamacite of meteoric irons by the shock of impact when the meteorite fell on the earth's surface. The prominent octahedral fracture and the distinct Neumann lines shown by the Piedade do Bagre meteorite give strong support to this view.

The following notes on the chemical analysis of the Piedade do Bagre meteoric iron have been supplied by Mr. M. H. Hey.

A piece of the meteorite free from rust and weighing 9.3032 grams was dissolved in hydrochloric acid. The residue (0.0034 gram) was boiled with aqua regia and left 0.0013 gram silica insoluble, which left no residue on evaporation with hydrofluoric and sulphuric acids. The aqua regia extract was evaporated to dryness, taken up with dilute hydrochloric acid, and added to the main bulk.

A little macerated filter paper was added and copper precipitated with hydrogen sulphide. The precipitate was dissolved in dilute nitric acid, the solution evaporated to dryness, taken up in water and a drop of nitric acid, and the copper determined colorimetrically with ammonia. The filtrate and washings were bulked to 1,000 c.c. after boiling off the hydrogen sulphide. The nickel was determined in two portions, one of 100 c.c. and one of 25 c.c., the iron being kept in solution by tartaric acid; to each portion was added an excess of sulphurous and tartaric acids, then the alcoholic solution of dimethylglyoxime, and finally excess of ammonia; found 7.44 and 7.56 %. Cobalt was determined on 50 c.c. as potassium cobaltinitrite.

It was found impossible to determine the iron accurately by double precipitation with ammonia and ammonium chloride, nickel being co-precipitated, but four precipitations, using a considerable excess of ammonia, gave a nickel-free ferric hydroxide. Satisfactory results were also obtained by a triple basic acetate precipitation. The first method gave 91.81 %, the second 92.35 %, using 25 c.c. of solution in each case. The first attempts at the iron estimation, by double ammonia precipitation, which gave high results owing to co-precipitation of nickel, were corrected by determining the nickel in the filtrate and then allowing a correction for that precipitated with the iron. Taking the total nickel at 7.44 %, the results were: Iron with some nickel, 94.20, 94.38, and 95.62 %; nickel in filtrate, 5.08, 4.54, and 3.15 %; hence iron (corrected), 92.10, 91.80, and 91.80 %. The first two determinations were carried out on 25 c.c. each of the solution, the third on a separate solution of 0.6305 gram of the meteorite dissolved in aqua regia.

Sulphur was determined on a third portion of 0.7034 gram of the meteorite, which was dissolved in strong nitric acid saturated with bromine in a flask, any

sulphur in the reaction gases being trapped in a wash-bottle filled with nitric acid and bromine, the solution in which was added to the main bulk after solution was complete. The bromine was then boiled off, and the sulphur (now present as sulphuric acid) precipitated as barium sulphate.

In taking the means, the first value for the nickel has been included twice, as more accurate, being found with 100 c.c. of solution; and the first two values for the iron also twice, the other three being found indirectly. The final results so obtained are:

Fe.	Ni.	Co.	Cu.	S.	P.	SiO ₂ .	Pt.	Total.
92.03	7.48	0.39	0.0097	0.22	trace ¹	0.01	trace ¹	100.14

¹ P less than 0.001 %; Pt less than 0.005 %.

The ratio of the percentage weight of Fe : Ni is 12.3 (and of Ni : Co, 19), which is in agreement with G. T. Prior's grouping for a medium octahedrite.¹

The specific gravity was determined by weighing the end-piece (2127.5 grams) in air and water to be 7.71 ± 0.02 , corrected $D_4^{18} = 7.69 \pm 0.02$.

List of Brazilian Meteorites.

A list of seven Brazilian meteorites was given by Orville A. Derby in 1888,² when he described four as new from the National Museum at Rio de Janeiro, and he mentioned some others that proved to be pseudo-meteorites or doubtful. The following list has been compiled from the British Museum Catalogue of Meteorites,³ with, of course, the addition of the new meteorite now described. Of the eighteen listed, ten are stones and seven irons, and one doubtful. Five are from Minas Geraes.

Angra dos Reis, Rio de Janeiro. Stone of $1\frac{1}{2}$ kg., fell January 30, 1869.
 Bendegó, Bahia. Iron of 5360 kg., found 1784.
 Bezerros, Pernambuco. Iron about 20 tons, fell May 9, 1915 [? no confirmation].
 Cratheus, Espirito Santo. Iron, found 1909 (?).
 Itapicuru-Mirim, Maranhão. Stone of 2 kg., fell March, 1879.
 Macao, Rio Grande do Norte. Shower of stones, fell November 11, 1879.
 Minas Geraes. Stone of 1.2 kg., known in 1888.
 Monte Alto, Bahia. Iron, known in 1888 [? no confirmation].
 Morro do Rocio, Santa Catharina. Stone, known before 1927.
 Piedade do Bagre, Minas Geraes. Iron, 59 kg., found 1922.
 Ponta Grossa, Paraná. Stone of 667 grams, fell April, 1846.

¹ G. T. Prior, *Min. Mag.*, 1920, vol. 19, p. 55.

² O. A. Derby, *Notas sobre meteoritos Brasileiros*. *Revista do Observatorio*, Rio de Janeiro, 1888, vol. 3, pp. 3-6, 17-20, 33-37. An abstract of this paper was given in *Amer. Journ. Sci.*, 1888, ser. 3, vol. 36, p. 157.

³ G. T. Prior, 1923; Appendix, 1927.

Santa Barbara, Rio Grande do Sul. Stone of 400 grams, fell September 26, 1873.

Santa Catharina. Iron, several masses, about 25 tons, found 1875.

Santa Luzia, Goyaz. Iron of $4\frac{1}{2}$ kg., found in 1921.

São Sébastião da Boa Vista,¹ Minas Geraes. An enormous meteorite, fell 1914 [? no confirmation].

Serra de Magé, Pernambuco. Shower of small stones, fell October 1, 1923.

Sete Lagoas, Minas Geraes. Six small stones, fell December 15, 1908.

Uberaba, Minas Geraes. Stone of $1\frac{1}{2}$ kg., fell June 29, 1903.

Others listed by O. A. Derby as pseudo-meteorites or as doubtful are :

Areado, Minas Geraes.

Curitiba, Paraná.

Curvello, Minas Geraes.

Morro do Chapéo, Bahia.

Pernambuco.

A circumstantial account of the fall of a meteorite near Curvello in Minas Geraes on 11 April 1833 has been given by P. Claussen.² At 6.45 in the evening of that day in Curvello he saw for the period of half a second a luminous meteor with an apparent diameter equal to that of the moon moving rather quickly in a direction from SSW. to NNE. and leaving a long luminous trail. When almost overhead it burst into three large pieces and several smaller ones and then disappeared. After the disappearance he counted 123 pulsations and then there were violent detonations followed by loud roarings lasting for three minutes. The meteor was also seen and heard at Diamantina (110 km. distant) and at Sabará (140 km.). At the same time a large 'stone' fell in a deep swamp on the Matto Grosso estate, 15 km. ESE. of Curvello, and a branch of a tree near the house was broken off. The proprietor caused a search to be made by his negroes, but nothing was found. However, a few days later a negro brought to Claussen a piece of metal, thought to be silver, which weighed about three ounces [i. e. 85 grams, if the ounces were English avoirdupois]. This Claussen acquired and placed in the National Museum at Rio de Janeiro. He further remarks that on 15 August 1834 he heard at Curvello similar detonations, but on this occasion a fall was not observed.

¹ Incorrectly listed as 'San Sebastiano da Boa Vista'.

² P. Claussen, Notes géologiques sur la province de Minas Geraes au Brésil. Bull. Acad. Sci. Bruxelles, 1841, vol. 8, pt. 1, pp. 322-343. (Fer météorique, pp. 341-343.)

Curvello came to be listed as a definite meteorite fall by Otto Buchner¹ in 1863; he gave the weight as 170 grams [i. e. just double 85 grams], and he thought that the meteorite was more probably a stone than an iron. Later, Orville A. Derby² found in the Rio de Janeiro Museum a piece of iron weighing 218 grams without any information, but which was presumed to be the piece deposited by Claussen. A fragment of this was sent for examination to A. Brezina³ in Vienna, who previously had cast doubts on the authenticity of the meteorite; and it was afterwards in 1888 stated by Derby to be artificial iron. E. A. Wülfing⁴ in 1897 says that it was possibly a pseudo-meteorite and presumably lost.

The above has been given in some detail because it may perhaps have some bearing on the meteorite now described. The name Piedade do Bagre has here been decided upon, rather than Curvello (which had indeed been used provisionally before the above account was found in the literature), in order to avoid any possible confusion. It is, however, quite possible that this is part of the meteor so graphically described by Claussen.

EXPLANATION OF PLATES XI AND XII.

Meteoric iron of Piedade do Bagre, Minas Geraes, Brazil.

FIG. 5. Third view of the mass, with the ridge in fig. 3 on top and the projecting corner showing the natural octahedral fracture to the right. $\times \frac{1}{4}$.

FIG. 6. Closer view of the natural octahedral fracture. Actual size.

FIG. 7. Polished and etched surface nearly parallel to an octahedral face. Slightly reduced (size of specimen $12\frac{1}{2} \times 9$ cm.).

FIG. 8. Neumann lines in the kamacite bands. The area magnified is outlined in fig. 7. $\times 10$.

¹ O. Buchner, *Die Meteoriten in Sammlungen*. Leipzig, 1863, p. 56.

² O. A. Derby, *loc. cit.*, 1888, pp. 35-36.

³ A. Brezina, *Die Meteoritensammlung des k.k. mineralogischen Hofkabinetes in Wien am 1. Mai 1885*. Jahrb. Geol. Reichsanst. Wien, 1885, vol. 35, pp. 151-276. (Curvello in the Appendix on p. 221.)

⁴ E. A. Wülfing, *Die Meteoriten in Sammlungen*. Tübingen, 1897, p. 399.

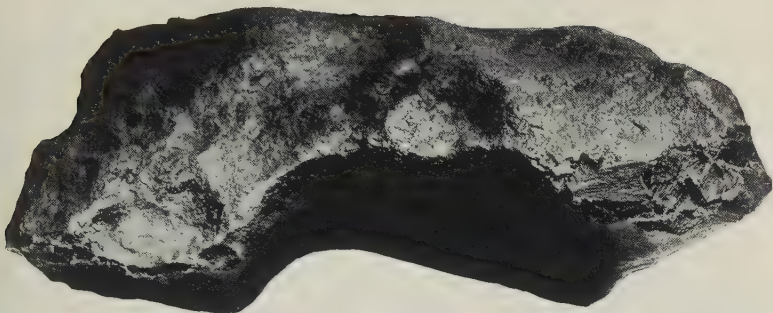


FIG. 5.



FIG. 6.

L. J. SPENCER: METEORIC IRON OF PIEDADE DO BAGRE
MINAS GERAES. BRAZIL.

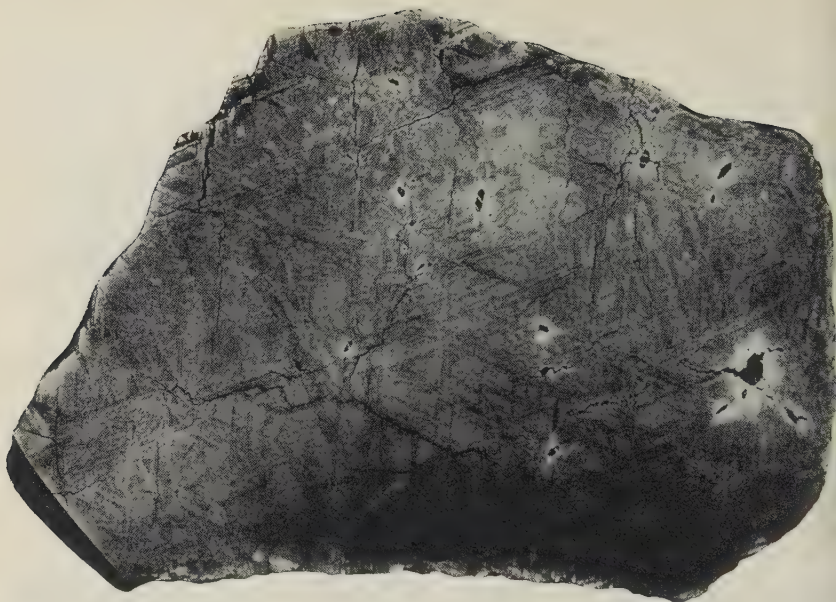


FIG. 7.



FIG. 8.

L. J. SPENCER: METEORIC IRON OF PIEDADE DO BAGRE
MINAS GERAES, BRAZIL.

On face- and zone-symbols referred to hexagonal axes.

By MAX H. HEY, B.A., B.Sc.

Assistant-Keeper in the Mineral Department of the
British Museum of Natural History.

[Read June 3, 1930.]

THE axial system of Bravais, with three co-planar axes at 120° to one another and a fourth at right angles to them is almost universally adopted for the description of crystals based on the hexagonal prism as unit cell. But it does not seem to have been generally recognized that the use of these axes entails some complications in respect of face- and zone-symbols. These it is the purpose of the present note to consider.

If we take any pair of faces, say $(10\bar{1}2)$ and $(01\bar{1}3)$ and cross-multiply in the usual way, dropping the third index, we obtain a three-index symbol for the zone, $[23\bar{1}]$. We cannot write in the third index equal to *minus* the sum of the first two, for if we do, the Weiss zone law is only obeyed provided we drop this third index again, a clearly incorrect result. Thus, taking the face $(10\bar{1}2)$, we have: $[23\bar{1}] \times (10\bar{1}2) = 2 + 0 - 2 = 0$, but $2 + 5 - 2 \neq 0$, and $0 + 5 - 2 \neq 0$, and $2 + 0 + 5 - 2 \neq 0$. In fact, the symbol $[23\bar{1}]$ is complete in itself, and does not include a third index. For convenience, a dagger mark $\dagger$ is used throughout this note to indicate which index is 'absent' in this way; while an asterisk $*$ is used to indicate the position of an index which has been merely 'dropped' for cross-multiplication, &c.

Moreover, if instead of the third we drop the second index and cross-multiply, the zone-symbol becomes $[1\dagger 31]$; and if we drop the first index, it becomes $[\dagger 1\bar{2}\bar{1}]$.

$$\begin{array}{r} 1 \mid 0 \mid 2 \mid 2 \\ 0 \mid 1 \mid 3 \mid 3 \\ \hline [23\dagger\bar{1}] \end{array}$$

$$\begin{array}{r} 1 \mid * \bar{1} 2 \mid 1 \mid 2 \\ 0 \mid * \bar{1} 3 \mid 0 \mid 3 \\ \hline [1\dagger 31] \end{array}$$

$$\begin{array}{r} * 0 \mid \bar{1} 2 \mid 0 \mid 2 \\ * 1 \mid \bar{1} 3 \mid 1 \mid 3 \\ \hline [\dagger 1\bar{2}\bar{1}] \end{array}$$

Finally, we may deduce the zone-symbol from the gnomonic projection by noting the points at which the zone-line cuts the

crystallographic axes; or from the linear projection by noting the points at which the normals from the zone-point on to the axes cut the latter. On the gnomonic projection, these points are 2, $\frac{1}{2}$, and $-2/5$ (fig. 1); taking their reciprocals and adding -1 as the unique index, we get $[\frac{1}{2}, 2, -5/2, -1]$, and clearing the fractions $[14\bar{5}\bar{2}]$. On the linear projection, the points $\frac{1}{2}, 2, -2\frac{1}{2}$ give with -1 as fourth index, after clearing of fractions, $[14\bar{5}\bar{2}]$. This time we have obtained a four-index symbol for the zone, and, moreover, one which obeys the rule that each of the first three indices is equal to *minus* the sum of the other two.

Even now the complexities are not exhausted. We rejected the four-index symbol $[23\bar{5}\bar{1}]$ derived from $[23\bar{1}\bar{1}]$ by writing in the third index $i = -(h+k)$ because it did not obey the Weiss zone-law. Equally we are compelled to reject the symbols $[14\bar{3}1]$ and $[11\bar{2}\bar{1}]$ derived similarly from $[1\bar{1}31]$ and $[1\bar{1}\bar{2}\bar{1}]$. Now the three three-index symbols do obey the Weiss zone-law; but the four-index symbol $[14\bar{5}\bar{2}]$, derived from the gnomonic or the linear projection, does not, whether we use all four indices or drop the first, second, or third. It does, however, obey a modified law. The Weiss zone-law is suitable for a three-axis system such as is used in the other crystallographic systems, or obtained by dropping one of the three co-planar axes of the hexagonal system in the above three-index symbols. To make it applicable where there are three co-planar axes we must apply a factor of $3/2$ to the unique index, and the zone-symbol $[14\bar{5}\bar{2}]$ then obeys this modified law; e.g. taking the face $(10\bar{1}2)$, $1+0+5-4 \times 3/2 = 0$.

The four-index symbol has a simple relation to the three three-index symbols for the zone. If we write the three-index symbols so that they all have the same last index, and then sum them, index for index, taking, however, only $2/3$ of the sum for the last index, we have the four-index symbol: $[2-1, 3+1, -3-2, 2/3 \times (-1)] = [14\bar{5}\bar{2}]$.

It is also possible to deduce the three-index symbols from the gnomonic or the linear projection. OA_1, OA_2 , and OA_3 are the three co-planar axes (fig. 1); if OA_3 is to be dropped, giving a symbol of the form $[UV\bar{1}W]$, let Oa_1, Oa_2 bisect the angles A_1OA_3, A_2OA_3 and take the points where the gnomonic zone-line cuts these special axes, $\frac{1}{2}, 1/3$; take reciprocals, add -1 as third index, and clear of fractions; we then get $[23\bar{1}\bar{1}]$. Or take the points where the normals from the linear zone-point on these axes cut them, 2, 3; adding -1 as third index, we have $[23\bar{1}\bar{1}]$.

We may now proceed to generalize these relations. Consider two faces $(h, k, \bar{h} + \bar{k}, l)$ and $(p, q, \bar{p} + \bar{q}, s)$; cross-multiplying, we have the three-index symbols $[ql - ks, hs - pl, \dagger, pk - hq]$, $[pl + ql - hs - ks, \dagger, pl - hs, pk - hq]$, and $[\dagger, hs + ks - pl - ql, ks - ql, pk - hq]$. By summation in the above manner we have a four-index symbol $[2ql + pl - 2ks - hs, 2hs + ks - 2pl - ql, pl - ql - hs + ks, 2pk - 2hq]$. The

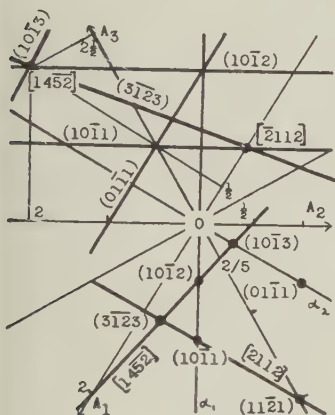


FIG. 1.

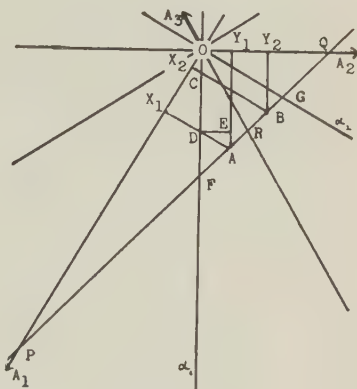


FIG. 2.

FIG. 1. Gnomonic (below) and linear (above) projections showing the derivation of the zone-symbol $[145\bar{2}]$ and the face-symbol $(3\bar{1}2\bar{3})$. On a radius of projection of 1.25 cm. For $[2112]$ read $[2\bar{1}12]$; for $(10\bar{1}3)$ read $(01\bar{1}3)$.

FIG. 2. Gnomonic projection showing the derivation of the four-index symbol for the general zone $[hkil : pgrs] = [A : B]$.

The orientation adopted in these projections is that used by Dana, Groth, Tutton, Lewis, and Miers. A clockwise arrangement of the axes was used by A. Bravais (1851, 1866). V. Goldschmidt has two orientations. For the relation between the hexagonal and rhombohedral axes at least three different methods have unfortunately been in common use.

three three-index symbols obey the ordinary Weiss zone-law; the four-index symbol obeys the modified law given above. For example, taking the face $(h, k, \bar{h} + \bar{k}, l)$:

- (i) $hlq + hks - hks - klp + klp - hlq = 0$.
- (ii) $hlp + hlq - h^2s - hks - hlp + h^2s - klp + hks + klp - hlq = 0$.
- (iii) $hks + k^2s - klp - klq - hks + hlq - k^2s + klq + klp - hlq = 0$.
- (iv) $2hlq + hlp - 2hks - h^2s + 2hks + k^2s - 2klp - klq - hlp + hlq + h^2s - hks - klp + klq + hks - k^2s + 3/2(2klp - 2hlq) = 0$.

We must now ascertain whether the same symbols are derivable from the gnomonic or the linear projection. Let A, B (fig. 2) be any two faces $(h, k, \bar{h} + \bar{k}, l)$ and $(p, q, \bar{p} + \bar{q}, s)$, in gnomonic projection. It is required to find the symbol of the zone-line AB . Let this cut the axes of A_1, A_2 , and A_3 at P, Q , and R respectively, then $[1/OP, 1/OQ, -1/OR, -1]$ is the required symbol. Let AX_1, AY_1, AZ_1 be normals from A on the three axes, and BX_2, BY_2, BZ_2 normals from B . Then $OX_1 = h/l, OY_1 = k/l, OX_2 = p/s$, &c. Now by similar triangles $\frac{OP - h/l}{OP - p/s} = \frac{PX_1}{PX_2} = \frac{AX_1}{BX_2}$. Let OD be a line parallel to AY_1 , cutting AX_1 in D , and DE a line parallel to OY_1 , cutting AY_1 in E . Then

$AX_1 = DX_1 + AD = h/l \cdot \tan 30^\circ + DE \cdot \sec 30^\circ = 1/\sqrt{3} \cdot h/l + 2\sqrt{3} \cdot k/l$, since $\angle DOY_1$ is a right angle and angle $A_1OA_2 = 120^\circ$.

Similarly, $BX_2 = 1/\sqrt{3} \cdot 1/s \cdot (p + 2q)$.

$$\begin{aligned} \text{Hence, } \frac{OP - h/l}{OP - p/s} &= \frac{1/\sqrt{3} \cdot 1/l \cdot (h + 2k)}{1/\sqrt{3} \cdot 1/s \cdot (p + 2q)}, \\ (OP - h/l)(lp + 2lq) &= (OP - p/s)(hs + 2ks), \\ (lp + 2lq - hs - 2ks)OP &= hp + 2hq - hp - 2qp, \\ \frac{1}{OP} &= \frac{2lq + lp - 2ks - hs}{2hq - 2kp}. \end{aligned}$$

$$\text{Similarly, } \frac{1}{OQ} = \frac{2hs + ks - 2lp - lq}{2hq - 2kp}.$$

And since PQR is a straight line and the angles POR, QOR are 60° , OR is a harmonic mean between OP and OQ , that is, $1/OR = 1/OP + 1/OQ$.

Thus the symbol is $[2ql + pl - 2ks - hs, 2hs + ks - 2pl - ql, pl - ql - hs + ks, 2pk - 2hq]$, identical with the above. That the same symbol is also derived from the linear projection is equally readily shown.

The three-index symbols may also be derived from the gnomonic or the linear projection, as outlined above. Taking the general case of fig. 2 again, let QRP cut Oa_1 in F and Oa_2 in G , and let BX_2 cut Oa_1 in C (AX_1 cuts it in D). The required symbol is $[1/OF, 1/OG, \dagger, \bar{1}]$.

$$\text{By similar triangles, } \frac{OF - OC}{OF - OD} = \frac{BC}{AD}.$$

We know

$$OC = p/s \cdot \sec 30^\circ, OD = h/l \cdot \sec 30^\circ, BC = q/s \cdot \sec 30^\circ, AD = k/l \cdot \sec 30^\circ.$$

$$\text{Thence, } \frac{OF - p/s \cdot \sec 30^\circ}{OF - h/l \cdot \sec 30^\circ} = \frac{q/s \cdot \sec 30^\circ}{k/l \cdot \sec 30^\circ},$$

$$OF(k/l - q/s) = kp/sl.\sec 30^\circ - hq/sl.\sec 30^\circ,$$

$$\frac{1}{OF} = \frac{(ks - ql).\sec 30^\circ}{kp - hq}$$

But the unit along Oa_1 is the distance O to $(10\bar{1}1)$ and is $\sec 30^\circ$ times the unit along OA_1 , which is O to $(2\bar{1}\bar{1}2)$, so that in terms of the latter unit, $\frac{1}{OF} = \frac{ks - ql}{kp - hq}$, and $\frac{1}{OG} = \frac{lp - hs}{kp - hq}$.

This gives a symbol $[lq - ks, hs - lp, \dagger, hq - kp]$, identical with the above; and the other three-index symbols are derived similarly.

Between the four symbols of any zone, simple transformation relations may easily be discovered. If the three-index symbol obtained by cross-multiplication in the usual way, omitting the third index, be $[UV\dagger W]$, the other three-index symbols are $[U - V, \dagger, -V, W]$, and $[\dagger, V - U, -U, W]$, and the four-index symbol is $[2U - V, 2V - U, -U - V, 2W]$. Or, if the four-index symbol be $[u, v, \bar{u} + \bar{v}, w]$, the three-index symbols are

$$\left[\frac{2u+v}{3}, \frac{2v+u}{3}, \dagger, \frac{w}{2} \right], \quad \left[\frac{u-v}{3}, \dagger, -\frac{2v+u}{3}, \frac{w}{2} \right],$$

$$\text{and} \quad \left[\dagger, \frac{v-u}{3}, -\frac{2u+v}{3}, \frac{w}{2} \right].$$

Consider now the above zone $[14\bar{5}\bar{2}]$ and the zone $[\bar{2}112]$, which may also be written $[10\dagger\bar{1}]$, $[1\dagger 0\bar{1}]$, or $[\dagger 111]$. By cross-multiplication of their three-index symbols, in the proper pairs, we have the same four-index symbol for the face in each case:

$\begin{array}{r} 1\,0\dagger\bar{1}\,10\,\bar{1} \\ 2\,3\dagger\bar{1}\,23\,\bar{1} \\ \hline 3\bar{1}*3 \\ (3\bar{1}\bar{2}3) \end{array}$	$\begin{array}{r} 1\, \dagger 0\bar{1}\,10\,\bar{1} \\ 1\, \dagger 3113\,1 \\ \hline 3*\bar{2}3 \\ (3\bar{1}\bar{2}3) \end{array}$	$\begin{array}{r} \dagger 1\, \,1111\,1 \\ \dagger 1\, \,2\bar{1}\bar{1}\bar{2}\,\bar{1} \\ \hline *\bar{1}\bar{2}3 \\ (3\bar{1}\bar{2}3) \end{array}$
--	--	--

But if we cross-multiply the four-index zone-symbols, we obtain a set of three three-index face-symbols, bearing precisely the same relation to one another and to the four-index face-symbol as the three-index zone-symbols do to the four-index zone-symbol.

$\begin{array}{r} 1\,4*\bar{2}\bar{1}4\,\bar{2} \\ \bar{2}\,1*2\bar{2}\bar{1}\,2 \\ \hline (10, 2, \dagger, 9) \end{array}$	$\begin{array}{r} 1*\bar{5}\bar{2}\bar{1}\bar{5}\,\bar{2} \\ \bar{2}*12\bar{2}\bar{1}\,2 \\ \hline (8\dagger\bar{2}9) \end{array}$	$\begin{array}{r} *4\,\bar{5}\bar{2}4\bar{5}\,\bar{2} \\ *\bar{1}\,1211\,2 \\ \hline (\dagger, 8, 10, \bar{9}) \end{array}$
---	--	---

Then $(10+8, 2-8, -2-10, 9 \times 2) = (18, \bar{6}, \bar{12}, 18) = (3\bar{1}\bar{2}3)$; further $(10, 2, \dagger, 9) = (10-2, \dagger, -2, 9) = (8\dagger\bar{2}9)$, and again $(10, 2, \dagger, 9) = (\dagger, 2-10, -10, 9) = (\dagger, 8, 10, \bar{9})$.

The proof of the generalization of these relations and also of others parallel to those given above for the zone-symbols, to apply to the face-symbols, follows precisely the same lines as for the zone-symbol relations.

It is well known that if $(hkil)$ and $(pqrs)$ are any two faces, then $(mh+np, mk+nq, mi+nr, ml+ns)$ is a third face in the same zone, m and n being any rational numbers. The reciprocal relation of faces and zones in so many respects suggests that it should also hold for the four-index zone-symbols, and it is readily proved that this is the case. For let $[uvw]$, $[pqrs]$ be two zones. Cross-multiplying, $(qw-vs, us-wp, \dagger, vp-uw)$ is the face common to the two zones. Then if $[mp+nu, mq+nv, mr+nt, ms+nw]$ is a zone passing through this same face, we should have

$$mpqw - mpsv + nquw - nsuv + mqsu - mpqv + nsuv - npvw + mpsv - mqsu + npvw - nquw = 0.$$

As this is true, the relation is proved. A similar relation is easily shown between the three-index symbols of any three co-zonal faces or any three zones having a face in common.

Finally, as we have found the Weiss zone-law to govern the combination of a three-index zone-symbol with a four-index face-symbol or a three-index face-symbol with a four-index zone-symbol, and a simple modification to govern the combination of four-index face- and zone-symbols, we may inquire whether we can find a corresponding relation for the combination of three-index face- and zone-symbols. Such a relation can indeed be found, but it is not so simple as either of the other laws. Consider the pair of faces $(hkil)$ and $(pqrs)$; by cross-multiplication we find that the zone defined by the two faces is $[ks-ql, lp-hs, \dagger, hq-kp]$. And the three-index symbol (with A_3 missing) of $(hkil)$ is

$$\left(\frac{2h+k}{3}, \frac{2k+h}{3}, \dagger, \frac{l}{2} \right).$$

Combining the two in the ordinary way we have

$$\begin{aligned} & 1/3.(2h+k)(ks-ql) + 1/3.(2k+h)(lp-hs) + \frac{1}{2}l.(hq-kp) \\ &= 2/3.hks + 1/3.k^2s - 2/3.hlq - 1/3.klq + 2/3.klp + 1/3.hlp - 2/3.hks \\ & \quad - 1/3.h^2s + \frac{1}{2}.hlq - \frac{1}{2}.klp \\ &= 1/3.k^2s - 1/3.h^2s - 1/6.hlq + 1/6.klp - 1/3.klq + 1/3.hlp \end{aligned}$$

$$\begin{aligned}
&= 1/3.k(ks - ql) + 1/3.h(lp - hs) + 1/6.klp - 1/6.hlq \\
&= (ks - ql)(k/3 + h/6) - khs/6 + (lp - hs)(h/3 + k/6) + khs/6 \\
&= \frac{1}{2} \left\{ (ks - ql) \left(\frac{2k + h}{3} \right) + (lp - hs) \left(\frac{2h + k}{3} \right) \right\}.
\end{aligned}$$

That is, after combining the two three-index symbols in the ordinary way, we have an excess equal to half the sum of the products of the first index of each by the second index of the other. In other words, if $(HK\uparrow L)$ is a face in the zone $[UV\uparrow W]$, then the law corresponding to the Weiss zone-law is $HU + KV + LW - \frac{1}{2}(HV + KU) = 0$.

These generalizations, which do not appear to have been previously noticed, show a symmetrical equality of the three co-planar axes, and exhibit the reciprocal relation of zones and faces in a marked degree. And they clear up the apparent contradiction between the zone-symbol as deduced by cross-multiplication, dropping different indices, and as deduced from the gnomonic projection, which has been a source of considerable perplexity to the author from time to time.

The relations may be summed up as follows:

To every face or zone of a crystal referred to the Bravais hexagonal four-axis system there belong four different face or zone-symbols.

Each face-symbol as usually deduced from the gnomonic or the linear projection is the four-index face-symbol in common use.

A four-index zone-symbol may be deduced from the gnomonic or the linear projection, and is not the zone-symbol in common use.

The four-index symbols, both of zones and faces, obey the relation that the sum of the first three indices is zero.

Cross-multiplication of a pair of four-index face- or zone-symbols gives three different zone- or face-symbols according to which pair of indices is dropped before cross-multiplication.

The three-index zone-symbol with third index absent is the zone-symbol in common use, but a system of three-index face-symbols is of no practical use.

These three-index symbols are complete in themselves, and a fourth index cannot be introduced by the rule $i = -(h + k)$.

Cross-multiplication of a corresponding pair of three-index face- or zone-symbols gives, after introduction of the proper index by the rule that the sum of the first three indices is zero, a four-index zone- or face-symbol.

The three-index face- and zone-symbols can also be deduced from the gnomonic projection; if it is proposed to derive the symbol with

third index absent, the face-poles and zone-lines are referred to a pair of axes bisecting the angles between $-A_3, A_1$ and $-A_3, A_2$. The linear projection can be similarly treated.

The three-index symbols of any face (pqr s) or zone [pqr s] are

$$\left[\left(\frac{2p+q}{3}, \frac{2q+p}{3}, \dagger, \frac{s}{2} \right) \right], \left[\left(\frac{p-q}{3}, \dagger, -\frac{2q+p}{3}, \frac{s}{2} \right) \right]$$

and
$$\left[\left(\dagger, \frac{q-p}{3}, -\frac{2p+q}{3}, \frac{s}{2} \right) \right].$$

The sign $[()]$ indicating zone or face.

The four-index symbol of any face ($PQ\dagger S$) or zone [$PQ\dagger S$] is $[(2P-Q, 2Q-P, -P-Q, 2S)]$, and the remaining two three-index symbols are $[(P-Q, \dagger, -Q, S)]$ and $[(\dagger, Q-P, -P, S)]$.

If the three-index symbols of any face or zone are first written so as to have the same last index, and then summed, index for index, but taking only $2/3$ the sum for the last index, the result is the four-index symbol of the face or zone.

If the three-index symbol of a zone or face is combined with the four-index symbol of a face or zone, dropping the appropriate index of the latter, the ordinary Weiss zone-law: $hu + kv + lw = 0$ is satisfied when the face belongs to the zone.

If the four-index symbol of a face ($hkil$) is combined with the four-index symbol of a zone [uvw], without dropping any index, a small modification of the Weiss zone-law is necessary, namely $hu + kv + it + \frac{3}{2}. lw = 0$. The factor $3/2$ is related to the presence of three co-planar axes.

The law corresponding to the Weiss zone-law governing the combination of a three-index face-symbol (e. g. ($HK\dagger L$)) with a corresponding three-index zone-symbol (e. g. [$UV\dagger W$]) is more complex, namely $HU + KV + LW - \frac{1}{2}(KU + HV) = 0$.

If ($hkil$) and (pqr s) are any two faces, it is well known that ($mh + np, mk + nq, mi + nr, ml + ns$) is a co-zonal face, m and n being any rational numbers. A precisely parallel relation holds between the four-index symbols of any three zones having a face in common.

A precisely similar relation also holds between the three-index symbols of any three co-zonal faces or any three zones having a face in common.

MINERALOGICAL SOCIETY PUBLICATIONS

The Publisher is Mr. Humphrey Milford, Oxford University Press, *Amen House, Warwick Square, London, E.C. 4.*

Mineralogical Magazine.—Current Numbers price 6s. net each. Annual Subscription for four Numbers post free 20s., payable in advance to the Publisher, either direct or through any bookseller.

Back Numbers.—With the exception of Nos. 17, 18, 19, 21, and 22, which are out of print (and some few numbers of which the stock is low and which are reserved for the sets mentioned below), all numbers can be supplied separately at the following net rates: Nos. 1–48 at 4s. each; Nos. 49–111 at 5s. each; Nos. 112 (1926) onwards at 6s. each. Since 1920 (Vol. XIX) the Numbers have been issued quarterly, and include a separately-paged appendix of *Mineralogical Abstracts*.

Geological Map of the Shetland Islands (separate from Vol. II). Price, 4s. mounted, 2s. 6d. unmounted, net.

General Index to Vols. I–X, 4s.; to Vols. XI–XX, 6s. net.

Mineralogical Abstracts (Vol. I, Nos. 1–12, 1920–22, issued with Vol. XIX of the Magazine) are also sold separately. Price 2s. 6d. net each number. Later numbers (Vol. II, 1923–25; Vol. III, 1926–28; Vol. IV, 1929–) are issued only as part of the Magazine.

Bye-Laws and List of Members (1929). Price 1s. net.

Part sets at the following reduced rates. Set A.—Vols. I–X (Nos. 1–48, 1876–94, and Index No.) at 4s. per number less 15% (to Members of the Society less 35%). Set B.—Vols. XI–XX (Nos. 49–111, 1895–1925, and Index No.) at 5s. per number less 15% (to Members less 35%). Set C.—Vols. I–XX (Nos. 1–111 and two Index Nos.) at the above initial prices less 20% (to Members less 40%).

Proceedings of the Crystallogological Society [amalgamated with the Mineralogical Society in 1883]. Parts I and II (1877, 1882), price 4s. net each.

GENERAL NOTICES

Members desiring to propose Candidates for Election are requested to send the names and qualifications of the Candidates to the General Secretary, Mr. W. Campbell Smith, *British Museum of Natural History, South Kensington, London, S.W. 7*. There is an entrance fee of one guinea and the annual subscription is one guinea; the latter can be compounded for by a single payment of fifteen guineas. New Members, on the payment of their first subscription, receive all the numbers of the Magazine for the year for which the subscription is paid.

There are four meetings of the Society each year, on Tuesdays at 5.30 p.m. in January, March, June, and November. They are held (by kind permission) in the Apartments of the Geological Society, Burlington House, Piccadilly, London, W.1. Titles of papers to be read at these meetings, with a view to subsequent publication in the Magazine, should be sent to the General Secretary at least two weeks before the meeting. Authors alone are responsible for the views set forth in their respective papers. They are allowed, free of charge, fifty separate copies of their papers published in the Magazine.

MINERALOGICAL MAGAZINE

CONTENTS OF NO. 129

(June, 1930)

PAGE

F. C. PHILLIPS: Some mineralogical and chemical changes induced by progressive metamorphism in the Green Bed group of the Scottish Dalradian. (With Plate X)	239
J. M. SWEET: Notes on British barytes	257
L. J. SPENCER: A new meteoric iron from Piedade do Bagre, Minas Geraes, Brazil. With a chemical analysis by M. H. HEY. (With Plates XI and XII)	271
M. H. HEY: On face- and zone-symbols referred to hexagonal axes	283

MINERALOGICAL ABSTRACTS

(Vol. 4, No. 6, Pages 241-288)

Notices of Books (p. 241).—New Minerals (p. 244).—Colour of Minerals (p. 251).—Meteorites and Tektites (p. 257).—X-rays and Crystal-structure (p. 264).—Rock-forming Minerals and Petrology (p. 282).

PAGE	PAGE	PAGE	PAGE
ALVIR, A. D. 250	GALE, H. S. 244	LEHMANN, H. 256	SCHALLER, W. T. 245
ANGEL, F. 284	GARRABOS, L. 275	LOKKA, I. 249	SCHLOSSMACHER, K. 255
ARM, M. 271	GEORGE, W. H. 266	LUYTEN, W. J. 261	SEKITO, S. 268
ARMSTRONG, A. H. 271	GONYER, F. A. 262	MACCARTHY, G. R. 251	SHAW, W. F. B. 266
BARNES, W. H. 273	GOSNER, R. 271, 276-7, 279-80	MACGREGOR, A. G. 288	SHULTZ, J. F. 269
BARTH, T. F. W. 286	GOTTFRIED, C. 265, 273	MACHATSCHKEI, F. 277	SIGNER, R. 281
BAYLEY, P. L. 254	GREENWOOD, G. 269	MARK, H. 282	SIMPSON, J. B. 288
BECKER, C. A. 257	GRUNER, J. W. 270, 276	MARR, J. E. 244	SMITH, T. H. 262
BOGGILD, O. B. 258	HABICH, G. 254	MAUGUIN, C. 267	STARRABBA, F. S. 249
BRADY, L. F. 263	HACQUAERT, A. L. 255	MERRILL, G. P. 257, 262	STAUDINGER, H. 281
BRAGG, W. L. 265, 278	HEINEMAN, R. E. S. 263	MÜHL, H. 256	STELLA
BRANDENBERGER, E. 273	HEINRICH, H. 257	MÜLLER, W. 288	STARRABBA, F. 249
BRILL, R. 267	HENDRICKS, S. B. 269	MUSSONUS, F. 276-7, 279-80	STUHLMAN, O. 254
BRINDLEY, G. W. 287-8, 278	HENGSTENBERG, J. 282	NAGELSCHMIDT, J. G. 273	TAKANÉ, K. 280
BUSZ, K. 250	HODGE-SMITH, T. 262	NAVARRO, L. F. 259	TECHIRWINSKY, P. N. 260, 263, 285
CARDOSO, G. M. 230	HOLMES, A. 244	NININGER, H. H. 263-4	TUSTON, A. E. H. 275-6
CHAPMAN, F. 264	HORNE, J. 243	NOLD, A. 267	UFER, H. 254
CHIRVINSKY, P. N. 260, 263, 285	IMORI, S. 247	OFTEDAL, I. 276	ULRIKH, F. 286
COX, E. G. 266	JAMES, R. W. 268	OGG, A. 276	WARREN, B. E. 278
CUVELIER, V. 248	JEFFERSON, M. E. 269	PALMER, L. A. 244	WEIGEL, O. 254
DANIEL, A. F. 254	JONG, W. F. DE 270	PARTIDGE, F. C. 248	WEINSTEIN, M. 242
DENAEYER, M. A. 288	KEPP, F. E. 248	PAULING, L. 271, 274	WHITLOCK, H. P. 265
DITTLER, E. 256	KERR, P. F. 247	PEACH, B. N. 243	WILD, G. O. 251
DOELTER, C. 252	KLEMM, R. 251, 252	PELZER, H. 267	WINCHELL, A. N. 241
EAKLE, A. S. 245	KOCH, S. 244	PRESTON, F. W. 285	WINCHELL, N. H. 241
EITEL, W. 256	KOLACZKOWSKA, M. 283	PRIZBRAM, K. 252-3	WOOD, R. G. 268
ERDMANSDORFFER, O. H. 284	KONOBIEJEWSKI, S. 268	REINHARD, M. 285	WYATT, J. 281
EYLES, V. A. 288	KÖZU, S. 280, 286-7	RIBA, J. M. 282	WYCKOFF, R. W. G. 268, 287
FEERNÄNDEZ, NAVARRO, L. 259	KRAUS, O. 279	RICHARD, S. 284	YOSHIKI, B. 287
FINLAY, I. 244	KRIEGER, P. 274	RIES, H. 243	YOSHIMURA, J. 247
FRIEDEL, G. 272	KSANDA, C. J. 269	RIITMANN, A. 282	ZACHARASEN, W. H. 276, 278, 280-1
FULLER, M. L. 270, 274	KULIK, L. A. 261	ROBERTS, H. S. 260	
	LABUNZOV, A. N. 246	ROSICKÝ, V. 242	
	LANGER, B. 256	ROSS, C. S. 247	

First printed in Great Britain, at the University Press, Oxford

Reprinted by photo-litho by Alden & Mowbray Ltd,

at the Alden Press, Oxford, 1970